REPORT NO. CG-M-4-79

REPORT TO THE PRESIDENT ON AN EVALUATION OF DEVICES AND TECHNIQUES TO IMPROVE MANEUVERING AND STOPPING ABILITIES OF LARGE TANK VESSELS

James C. Card, H. Paul Cojeen, John S. Spencer
and James P. Harmon

Ship Design Branch
Merchant Marine Technical Division
Office of Merchant Marine Safety
U.S. Coast Guard Headquarters

SEPTEMBER 1979
FINAL REPORT

PREPARED BY

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This report is identical to "U.S. Coast Guard Implementation of Presidential Initiative for an Evaluation of Devices and Techniques to Improve the Maneuvering and Stopping Abilities of Large Tank Vessels" forwarded to the Secretary of Transportation by the Commandant 11 September, and subsequently forwarded to the President on 20 November 1979.

16. Abstract

This report is the final in a series of five that were initiated by the President in his 17 March 1977 message to Congress on the reduction of marine oil pollution. The report presents the basic definitions of maneuvering and stopping abilities and an assessment of the maneuvering and stopping abilities of existing tank vessels as a function of deadweight, compared to those of dry cargo vessels. Using the methods for evaluating maneuvering abilities that are outlined, various devices that have been proposed were examined. The initial evaluation was based on the degree of improvement in the maneuvering ability, the cost and the effect on the design of the vessel for each device. A mathematical (simulation) model was employed to further evaluate the most promising devices. A description of each operational technique has been included. The evaluation of the operational techniques was performed primarily by reporting on various full scale tests. The findings indicate that good maneuvering characteristics can be achieved for tank vessels, but without some guidance or requirement, this is not generally considered in the design cycle for new ship construction.

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JOB

THE SECRETARY OF TRANSPORTATION
WASHINGTON, D.C. 20590

NOV 20 1979

MEMORANDUM TO THE PRESIDENT

Subject: A Report on Means to Improve Maneuvering and Stopping Ability of Large Tankers Required as a Result of Your March 17, 1977 Maritime Oil Pollution Message to Congress

This memorandum transmits the completed study on devices and techniques to improve maneuvering and stopping ability of large tank vessels you directed as part of the efforts to reduce maritime oil pollution. The study concentrated on the physical ability of a ship to respond to the will of a master. Maneuvering and stopping capabilities were examined for existing tankers of conventional design and for hypothetical tankers whose design included the addition of several devices. Various operational techniques to improve maneuverability were examined by different methods including real-time shiphandling simulators.

The study indicates that tankers are not unmaneuverable; although safety and reliability can be enhanced in design. However, there are no national or international standards which require maneuvering or stopping considerations in tanker design. Thus the Coast Guard will initiate rule-making to require that maneuvering and stopping capabilities of new tank vessels be addressed in the design process and measured after construction. Existing tankers will be evaluated using standards which have been verified by full-scale trials. Further action for existing tank ships will be based on that evaluation. In addition, this subject will be pursued internationally at the Intergovernmental Maritime Consultative Organization (IMCO) where the Ship Design and Equipment Subcommittee is currently dealing with maneuverability of tank vessels as an item of high priority.

Neil Goldschmidt
Secretary

UNITED STATES GOVERNMENT

DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD

Memorandum

G-CPE/83
16450.1

DATE 11 SEP 1979

SUBJECT: ACTION: Presidential Initiative to Reduce Maritime Oil Pollution; Report to the President on the Large Tanker Maneuvering Study

FROM : Admiral J. B. Hayes
Commandant, U. S. Coast Guard

J B Hayes

TO The Secretary
Thru: The Deputy Secretary

BACKGROUND:

The President's message to Congress on March 17, 1977, outlined six major initiatives and directed five additional studies to be undertaken in an effort to reduce maritime oil pollution. The initiatives were presented to the international community through the Intergovernmental Maritime Consultative Organization (IMCO). The studies were undertaken in an effort to identify the most promising programs and techniques to reduce maritime oil pollution. This is the last of the five studies, the first of which was forwarded to the President on May 1, 1978. In his August 2, 1979, Environmental Message to Congress the President referred to this tanker maneuvering study and told Congress that he expects the Coast Guard to report promptly its results.

DISCUSSION:

The study showed that maneuvering and stopping of large tankers can be improved through the use of various devices and techniques. It also showed that conventional large tankers can be designed to maneuver and to stop reliably and predictably without additional devices. However, there is no requirement for tanker designers to give special attention to optimizing maneuvering and stopping capability. Since ship design is a complex process involving many tradeoffs, there is no guarantee that maneuverability is adequately addressed in tanker design and construction. The Coast Guard is required by the Port and Tanker Safety Act of 1978 to prescribe requirements relating to "...improvements in vessel maneuvering and stopping ability..." The requirements of the law and concern for tanker safety and pollution prevention indicate that action is necessary.

Therefore, the Coast Guard has initiated a regulatory project to require the maneuvering and stopping capabilities of tankers to be addressed in the design process and measured after construction. This requirement will most likely take the form of maneuvering performance standards based on definitive maneuvers to be verified by full scale trials. An Advance Notice of Proposed Rulemaking will be published to solicit a wide range of comments and ideas for implementing the action.

ACTION: Presidential Initiative to Reduce Maritime Oil Pollution; Report to the President on the Large Tanker Maneuvering Study

RECOMMENDATION:

That you sign the memorandum to the President which forwards the study on or before September 21, 1979.

2 Attachments

EXECUTIVE SUMMARY

INTRODUCTION

In the Presidential Initiatives to reduce maritime oil pollution, the Coast Guard was charged with evaluating devices and operational techniques to improve maneuvering and stopping ability of large tankers with research to include the use of ship simulators. The purpose of this evaluation is to develop sufficient information for making decisions on further action to reduce accidental oil pollution resulting from vessel collision, ramming, and grounding (CRG) accidents by investigating the potential that various devices and operational techniques may have on the maneuvering and stopping ability of large tankers.

SCOPE

Ships are like other forms of transportation in that they need to be started, stopped, and steered safely. The art of doing this is called maneuvering or shiphandling. Successful shiphandling depends on three separate operations: acquiring the right information, making the right decisions, and performing the right maneuvers. This study concentrates on the third of these operations, which is the physical ability of a ship, as a mechanism, to respond to the will of the master. There are four measures of maneuverability that were examined in the study:

* Turning
* Course Keeping
* Course Changing
* Stopping

Using these as measures, maneuvering and stopping abilities were examined for existing tankers of conventional design and hypothetical tankers whose design included the addition of several devices. Various operational techniques to improve maneuvering were also examined. Several methods were used for the examination including real time shiphandling simulators.

FINDINGS AND CONCLUSIONS

* EXISTING VESSEL DESIGN

This study puts the maneuvering and stopping ability of existing tank vessels into proper perspective. Results from mathematical simulations and full scale trials of tank vessels show that tankers are not unmaneuverable, but that they can be handled in a reliable and predictable manner.

In comparing a typical large tanker of approximately 250,000 DWT (deadweight tons, the cargo carrying capacity of a ship) with a much smaller tanker of 40,000 DWT on a non-dimensional basis, the turning, course keeping, and course changing abilities are comparable, while the stopping distance relative to length for the large tanker is about twice that of the small tanker. Similar comparisons, again on a non-dimensional basis, with cargo ships have shown that large tankers turn better, do not have quite as good course changing and course keeping ability, and have about half the stopping ability. Although the maneuvering ability of large tank vessels has been somewhat maligned, it is comparable to that of smaller tankers and many cargo ships with the exception of ability to stop from full speed.

This is not to say that all tankers maneuver in the same way. The maneuvering characteristics of a tanker are determined by its physical dimensions, the shape of the hull, its power, and the size, type, and location of the rudder. With such design variables, the maneuvering characteristics of ships of conventional design vary widely. In some designs where the owner is concerned about maneuvering and is willing to pay for design studies, maneuvering capabilities have been enhanced. Such is the case with a recently built class of 400,000 DWT tankers. The owners were concerned that this new design be capable of adequate maneuvering. Design studies, simulations, and model tests were done to address this concern, and as a result the ships have very good maneuvering characteristics. On the other hand there are ships operating with marginal maneuvering characteristics. Certain classes of container ships have posed handling problems in some ports. Perhaps more consideration of maneuvering during the design phase of these vessels would have minimized the problem.

* CRG ACCIDENT RATE

The rate at which tankers larger than 100,000 DWT have been involved in CRG accidents has steadily declined since 1969. The design of tankers since then has not changed. This suggests that the waterway transportation system has become more accommodating of these large ships as experience with them is gained. While the accident rate has declined, recent casualties such as the collision between the 212,000 DWT AEGEAN CAPTAIN and the 280,000 DWT ATLANTIC EMPRESS on July 19, 1979, show that the problem has not been completely solved.

* TESTING MANEUVERABILITY

Three ways to test and evaluate tank vessel maneuvering and devices were investigated: model scale, full scale, and computer simulation (mathematical modeling). All were found valid and used to some degree in the study. Fast time computer simulation was the most flexible and inexpensive and therefore was the most widely used. Real time simulation, the most sophisticated form of computer simulation, was used in the tugboat evaluation to validate the fast time computer model. Real time simulation has unique capabilities to evaluate those aspects of maneuvering involving human behavior, but these capabilities have not yet been fully utilized. Fast time computer simulation will be a primary tool in future maneuvering studies.

* MANEUVERING DEVICES

The study showed that maneuvering characteristics can be affected by the addition of devices. A 280,000 DWT tanker with various devices was simulated for shallow water at a maximum speed of 8 knots, which is realistic for harbor or offshore port approaches. The only maneuvering characteristic which was improved by more than 20 percent when a device was added, was the accelerating turn, which had an improvement of 38 percent by using a bow thruster. Because the original ship's turning ability in the accelerating turn is excellent, a 38 percent decrease in advance is only slightly more than the width of the ship. None of the devices improved the course changing ability and only two devices, the twin screw/twin rudder and steerable Kort nozzle, affected both turning and stopping ability. Of the devices evaluated only four, bow thrusters, twin screws, controllable pitch propellers, and increased astern horsepower, are available for commercial installation on large tankships.

* OPERATIONAL MANEUVERING TECHNIQUES

Several techniques for improving the maneuvering characteristics of large tankers were examined. Most promising were new ways to use tugs, employing slower approach speeds, and turning in lieu of stopping when space permits. Tugboat utilization strategies such as tug escort and tug assistance, including braking tugs and rudder tugs at harbor speeds were shown to be effective ways to improve the maneuvering and stopping of large tankers. Slower approach speeds give the shiphandler the option of increasing thrust to produce the ship's best maneuvering condition in a potential accident situation. It also gives him more time to take evasive action.

* MANEUVERING IN RELATION TO CRG ACCIDENTS

There is no method (i.e. mathematical model, accident analysis, or enlightened wisdom) which provides satisfactory information to use in evaluating the potential change to accident risk as a result of maneuverability improvements. Nor is a method expected to be available in the near future. Therefore, there is no way to evaluate the effectiveness of maneuvering devices in reducing oil outflow from tank ships.

* CONGRESSIONAL MANDATES

The problems of accidental pollution and reduced safety associated with large tank vessels with less than adequate maneuvering and stopping ability must be addressed, but the tools necessary to satisfactorily do this are not available. Devices improve maneuvering, but not significantly. Tankers with these devices cost more than those without them, but their benefit cannot be quantified. A reliable cost/benefit analysis methodology for this has been needed since July 1972 when the Ports and Waterways Safety Act (PL 92-340) was passed. That law required the Coast Guard to:

> "...begin publication as soon as practicable of proposed rules and regulations setting forth minimum standards of

design, construction, alteration, and repair of the vessels... Such rules and regulations shall, to the extent possible, include but not be limited to standards to improve vessel manevering and stopping ability and otherwise reduce the possibility of collision, grounding or other accident..." (emphasis added)

The requirement remains in the Port and Tanker Safety Act of 1978 (PL 95-474).

* IMPLEMENTING THE LAW

Until now the Coast Guard has not proposed rules in this area, because rules did not appear justified. The Final Environmental Impact Statement Regulations for Tank Vessels Engaged in the Carriage of Oil in Domestic Trade sums up the previous Coast Guard position when stating why improvements in maneuvering and stopping ability were not included in the regulations. It states:

"Improvements in Maneuvering and Stopping Ability

Requirements for various construction features and equipment intended to improve vessel maneuvering and stopping ability (and thus reduce the possibility of an accident) have been rejected as part of these proposed regulations for the following reasons: such requirements are not included in the international standards in the 1973 Marine Pollution Convention; there are unresolved questions concerning their effectiveness in reducing accidents which must be cleared up before regulations are published; and the features and equipment available improve maneuvering and stopping ability of large tankers only marginally."

The situation is no different today. The same thing might be said five years from now. It is possible that no one will ever be able to predict with confidence the degree that certain devices will reduce the risk of CRG accidents. The question becomes, is there another way to address maneuvering and stopping ability of tank vessels? The answer is "yes."

This study has shown that tankers can be designed so that they maneuver reliably and predictably. However there are no national or international standards which require maneuvering or stopping ability of tank vessels to be considered in the design process. Designing a vessel is an iterative process which includes many compromises and trade-offs. If the naval architect does not have a definite requirement for maneuvering or stopping ability, which he does have for intact or damage stability, he is not likely to accomodate such a feature at the expense of other considerations such as lower resistance or reduced vibration. Maneuvering and stopping must be considered in the design process. Performance measures for maneuverability can be developed based on existing ships which have good maneuvering characteristics. This is similar to

some of the methods used to determine intact stability criteria. There must also be a way to confirm the maneuvering characteristics, so meaningful full scale maneuvering trials for each ship in a class must be done. The nature of performance standards and verification trials must be developed.

Perhaps the most effective contributions to the CRG problem can be made through improved training and other methods which reduce "human error." The operator of a ship must perform many functions during port entry and harbor navigation. He must have the ability to compensate for many quirks in the waterway transportation system. But this need not include a vessel with marginal maneuvering characteristics. The vessel's master or pilot should be able to depend on his ship to maneuver reliably and predictably, he should be able to know that his ship possesses adequate maneuvering characteristics, and he should intimately know what they are.

COAST GUARD ACTION

The Coast Guard has initiated a regulatory project to require the maneuvering and stopping capabilities of new tankers to be addressed in the design process and measured after construction. This requirement will most likely take the form of maneuvering performance standards based on definitive maneuvers to be verified by full scale trials. An Advance Notice of Proposed Rulemaking will be published to solicit a wide range of comments and ideas for implementing the action. Existing tankers will be evaluated using the standards developed. Further action for existing tankships will be based on that evaluation. The Coast Guard will also pursue this action internationally at the Intergovernmental Maritime Consultative Organization (IMCO), where the Ship Design and Equipment Subcommittee is currently dealing with maneuverability of tank vessels as an item of high priority.

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INTRODUCTION

BACKGROUND

In his March 17, 1977, message to Congress recommending measures to control the problem of oil pollution of the oceans, President Carter announced:

> "ADDITIONAL INITIATIVES
>
> "Along with the major actions just discussed, the President is directing the Secretary of Transportation, in cooperation with the Environmental Protection Agency and other appropriate agencies, to undertake several studies of other promising programs and techniques for reducing marine oil pollution. These studies will include:
> ... An evaluation of devices to improve maneuvering and stopping ability ^ large tankers, with research to include the use of a sh' simulator."

Oil pollution from tank vessels is a hazard to the marine environment and must be eliminated or controlled. Collisions, rammings and groundings (CRG) are a significant source of this pollution. The oil outflow from such accidents may be reduced either by reducing the number of accidents or by reducing the amount of oil outflow in each accident. A central question is, how can the number of CRG accidents be reduced? One solution which has been proposed is to improve the maneuvering and stopping capabilities of large tankers. The premise that has been suggested is: Since the ability of large tankers to maneuver is less than that for smaller tankers, improvements in the maneuvering and stopping capabilities of large tankers will reduce the risk of collision, ramming and grounding accidents and the resulting oil outflow. The premise must be tested, and if it is found valid, decisions will be made about how to use the information to reduce oil outflow. This study examines the validity of the premise.

OBJECTIVE

The objective of this Presidential Initiative is to reduce oil pollution and to improve vessel safety by avoiding collision, ramming, and grounding accidents of tank vessels. The purpose of this evaluation is to develop sufficient information for making decisions on further action to reduce accidental oil pollution resulting from vessel CRG accidents by investigating the potential that various devices and techniques may have on the maneuvering and stopping ability of large tankers. The use of shiphandling simulators as a tool in evaluating these devices is investigated. Later action might include rulemaking, engineering studies, research and development projects, or administrative action such as training facility agreements.

Section II
SCOPE

MANEUVERING AS PART OF THE COLLISION, RAMMING, AND GROUNDING PROBLEM

Ships are like automobiles in that they need to be started, stopped, and steered safely. The art of doing this is called maneuvering or shiphandling. Successful shiphandling depends on three separate operations: acquiring the right information, making the right decisions, and performing the right maneuvers. While these operations are simply stated, examination of shiphandling soon reveals its complex nature. For example, the operations are influenced by many factors including the capability of the person controlling the ship, the adequacy of the information he receives, the responsiveness of his ship (inherent maneuverability), the characteristics of the waterway, and the state of the environment. An attempt to organize the factors influencing shiphandling is shown in Figure 1, the Waterway Transportation System.

This system is similiar to the highway transportation system in that the vessel subsystem is like the automobile subsystem and the waterway subsystem is like the highway subsystem. Other examples of how the systems compare are shown in Table 1.

Most of the time the waterway system, like the highway system, works fine and ships deliver their cargoes without incident. Sometimes an accident occurs. How or why the system did not work as planned is not easily understood. The system complexity makes improvements to system weaknesses difficult to identify and implement.

Generally humans prefer not to deal with complex problems as they should be dealt with. Our society is faced with many complex problems, and in dealing with them, simplistic solutions are often proposed. The danger with such treatment is that the simplistic solutions often lead to bigger problems or are ineffective and costly. The role of inherent maneuverability must be placed in proper perspective with respect to the waterway transportation system so that simplistic solutions are not proposed for a complex problem. In particular, it is difficult to quantify how improving the inherent maneuverability of tank vessels through devices or techniques improves the system and reduces accidents. Figure 2 displays the relationship between the total solution for preventing collision, ramming, and grounding accidents and the partial solution offered by devices and techniques intended to improve the maneuvering and stopping ability of large tankers.

The significance of this partial solution relative to the total solution has been widely discussed. It has been stated that much of the collision, ramming, and grounding accidents of large tankers would be eliminated if devices such as bow thrusters and controllable pitch propellers were required. It has also been stated that such devices are of little or no help in preventing collision, ramming, and grounding accidents for such vessels. The

FIGURE I
WATERWAY TRANSPORTATION SYSTEM

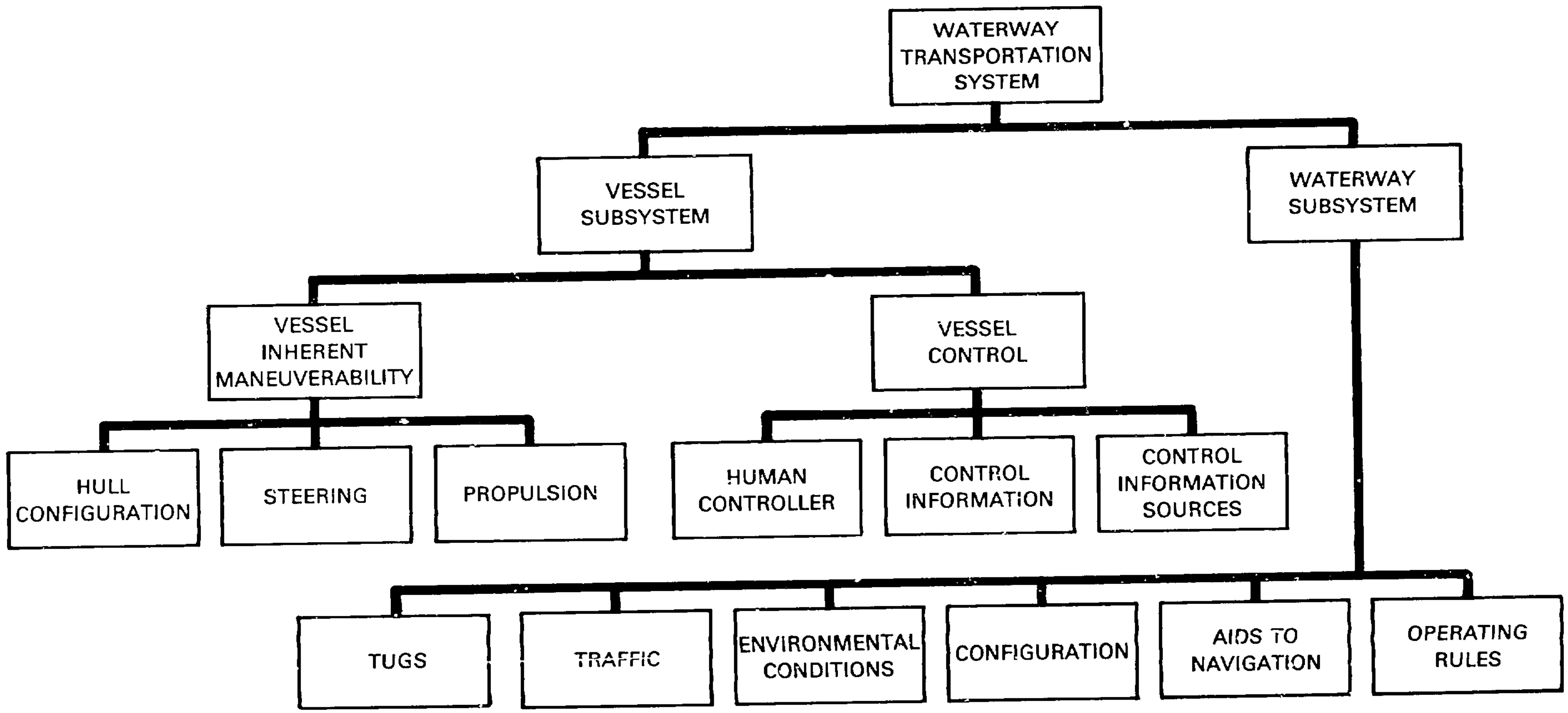


Table 1

Comparison of Vessel and Vehicle Subsystems

Vessel	Vehicle
* hull configuration * steering * propulsion	* shape and size of chassis * steering * engine, drive train and brakes
Vessel Control * human controller (pilot and mates) * control information (course, speed, current direction and speed, view of traffic) * sources of information (radar, speed log, gyro compass rate of turn indicator)	Vehicle Control * vehicle driver * control information (vehicle speed, distance from curb, view of traffic) * sources of information (speedometer, curb feelers, rear view mirror)
Traffic	Traffic
Environment Conditions (Wind, Rain, Fog, Tidal current)	Environmental Conditions (Same with the exception tidal current)
Configuration (channel depth and width, channel turns)	Configuration (curves in highway, shoulder width)
Aids to Navigation (buoys, light houses)	Road Markings (stop signs, yield signs, information on distance to next)
Rules of Road	Traffic Rules

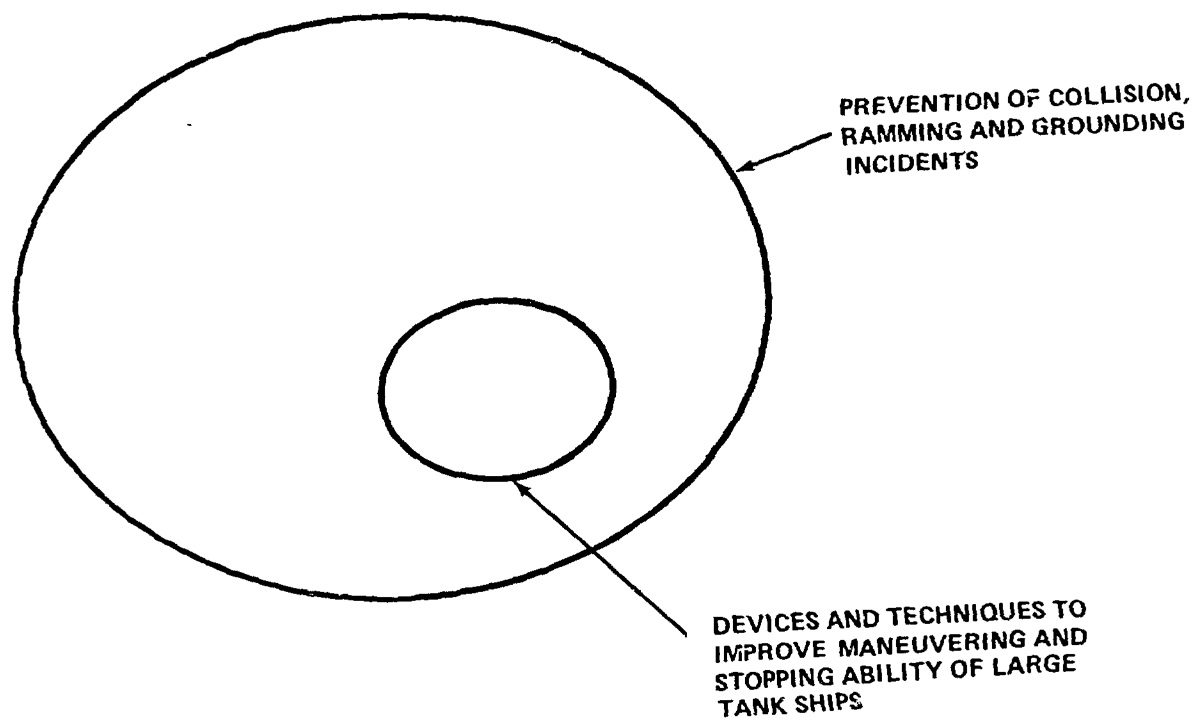


Figure 2 — Relationship *Among* the Topics that were Considered in the Study

truth is probably somewhere in between - the question is where.

This study concentrates on the inherent maneuverability portion of the waterway transportation system. This is described as the physical ability of a ship, as a mechanism, to respond to the will of the Captain.

APPROACH

The maneuvering problem was approached by first posing a series of questions which were then translated into study tasks. The tasks were compared with information which was already available to determine what additional work needed to be done. The questions were:

* What is meant by maneuvering and stopping ability?

* How are maneuvering and stopping ability related to the overall problem of vessel navigation, controllability, and shiphandling? Is there a relationship between maneuvering and stopping performance and the occurrence of accidents?

* What measures of performance can be used to evaluate maneuvering and stopping ability? How much maneuvering and stopping ability do large tank vessels presently have? How much do they need?

* What devices and techniques are available to improve maneuvering and stopping ability?

* How effective are these devices and techniques in producing improved maneuvering and stopping ability? What methods can be used to evaluate the potential change to maneuvering and stopping ability?

* What effect will changes to maneuvering and stopping ability have on risk of CRG accidents? What methods can be used to evaluate potential change to accident risk as a result of maneuverability improvements?

* What will the devices and techniques cost?

* How do the expected benefits compare to the costs?

Ideally this study would completely answer these questions, and regulatory or other action could be based on the answers. Practically, some of the questions are presently unanswerable, which had to be considered in designing the task statements. The study tasks developed were:

* Discuss overall vessel navigation controllability and shiphandling and how maneuvering and stopping ability is related.

* Define maneuvering and stopping ability.

* Determine maneuverability of existing ships.

* Identify devices and techniques and determine devices to be evaluated.

* Identify methods and procedures for evaluating devices and techniques.

* Determine effects of selected devices and techniques on maneuverability.

* Determine the costs of selected devices and techniques.

* Discuss methods to evaluate collision, ramming, and grounding accident risk as a function of maneuverability.

* Prepare the report.

At the beginning of the study it was recognized that a major job would be the compilation of work that had been completed or would be completed during the study. The literature is full of studies and reports on maneuvering. In addition, several recent Maritime Administration and Coast Guard efforts have a direct bearing on this study. The following recent work was identified as important to this study:

* Maneuvering Trials of the 278,000 DWT ESSO OSAKA in Shallow and Deep Waters (Sponsored by Coast Guard, Maritime Administration and American Institute of Merchant Shipping).

* Investigation into the Safety of Passage of Large Tankers in the Puget Sound Area (Sponsored by Coast Guard).

* Evaluation of Concepts for Improving the Inherent Controllability of Tank Vessels (Sponsored by Maritime Administration).

* Exploratory Tanker/Tug Maneuvering in Confined Waters (Sponsored by Coast Guard).

After review of the above efforts, the following additional work was necessary:

* Extend the analytical studies to additional vessels to evaluate concepts for improved controllability.

* Analyze casualties of large tank vessels.

* Determine the costs of devices and techniques.

* Conduct literature search.

* Evaluate maneuvering and stopping ability of existing merchant vessels.

The effort to extend the analytical studies, which were based on model tests of a twin screw configuration, was contracted to Hydronautics, Inc. The remainder of the work was done by the Coast Guard. Figure 3 shows the major pieces and how they fit into this report.

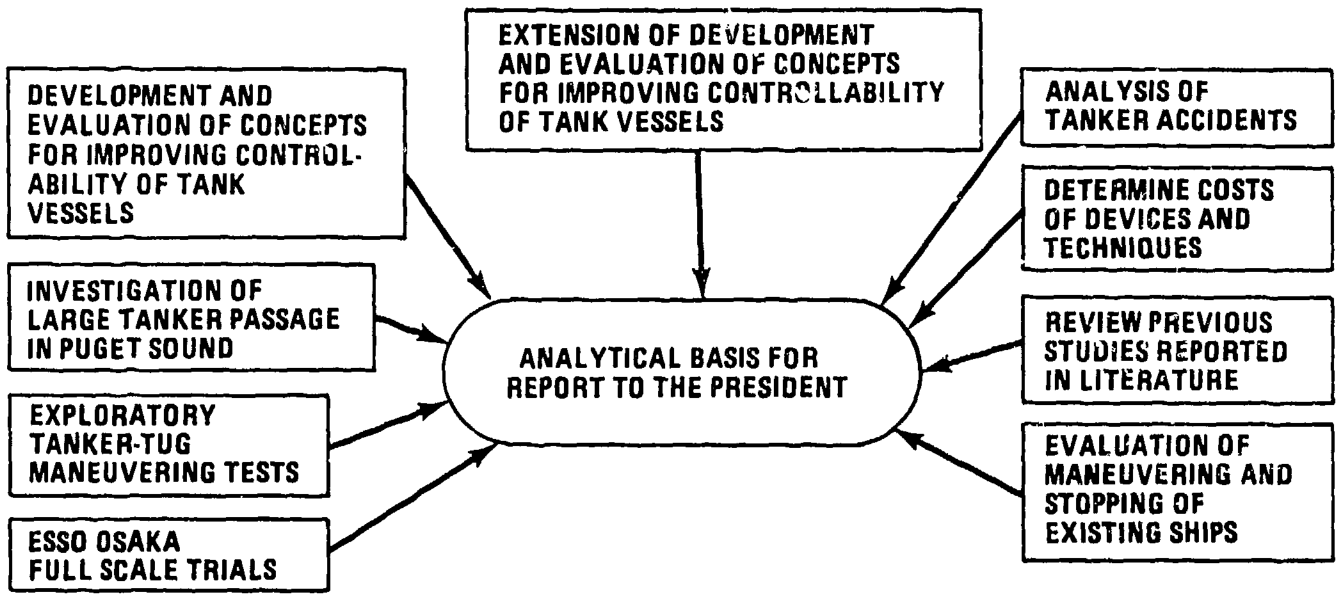


Figure 3 — Major Efforts Contributing to the Study of Large Tank Vessel Maneuvering and Stopping

Section III
MEASURES OF MANEUVERABILITY AND CONTROLLABILITY

Maneuverability has been described as the physical ability of a ship, as a mechanism, to respond to the will of the Captain. There are four measures of maneuverability that are examined in the following sections.

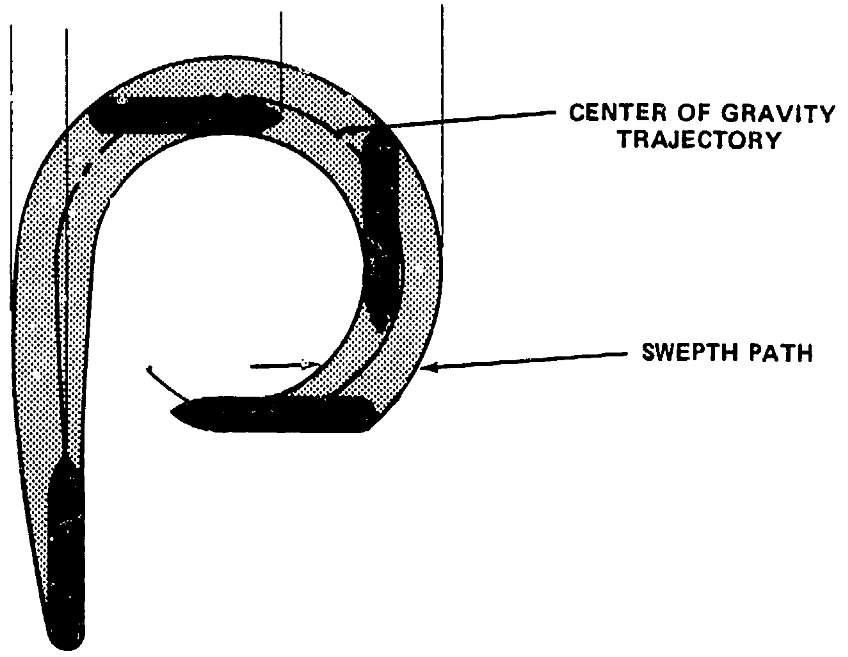
* Turning
* Course Keeping
* Course Changing
* Stopping

TURNING

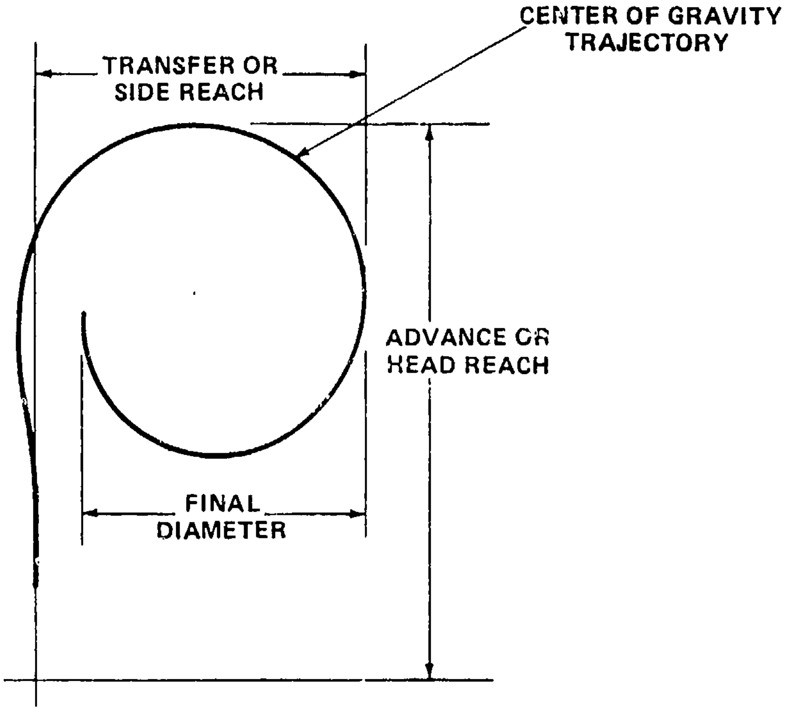
Turning ability is one aspect of vessel maneuverability that is not addressed in the literature nearly as much as stopping ability, but it is equally important. At operating speeds the turning radius of a vessel is the accepted measure of its turning ability. To improve turning ability, the diameter of the turning circle must be decreased. Turning radius is a function principally of vessel shape, length to beam ratio, and rudder forces. Tank vessels, as presently designed, have excellent turning ability mainly because of their full shape and low length to beam ratio.

The simplest way to turn a ship is to set the hull at an angle relative to the direction of advance; the hull then generates the necessary sideways force to turn. The purpose of the rudder is to set the main hull at the required angle. During a turn a ship's bow does not point in the precise direction in which the ship is moving, but measurably further in the direction of the turn, somewhat in the manner of a racing car cornering with a controlled skid. The ship sweeps out a path considerably wider than her own beam. Figure 4 illustrates this point for a 512,000 DWT tanker.

It has been found that the path of a turn does not change much with speed; that is, a ship moving slowly cannot turn in a smaller circle than when moving quickly. The ordinary single screw merchant ship has the rudder immediately aft of the propeller, where it employs the full benefit of the slip stream. As ship speed is reduced the slip stream falls also, and rudder forces decrease. In the absence of extraneous forces this still enables a course of constant curvature to be followed; but if wind and weather act on the ship, as speed approaches zero, they take complete charge; the rudder becomes useless and the ship drifts. However, at service speed, a single rudder, single screw vessel has excellent steering control.



(a) Center of Gravity Trajectory and Swepth Path



(b) Notation for Turning Circle Maneuver

Figure 4 – Turning Circle for Large Fully Loaded Tank Vessel in Deep Water with an Approach Speed of 15.2 Knots. (Excerpted from an Owner Supplied Chart Placed in the Pilot House for Use by the Navigating Officers.)

COURSE KEEPING

Course keeping ability, sometimes called course stability, refers to the ability of a vessel to maintain a straight course with minimum rudder action. One of the concerns about large tanker maneuverability has been course stability. In reality, course keeping is not related to hydrodynamic stability alone, but is a function of the combined system consisting of the ship and its control. There are two technical aspects of ship behavior which must be understood in a description of maneuverability. These are directional stability and hydrodynamic or dynamic stability. Directional stability refers to the ability of a ship to maintain a straight course when the rudder motions needed to compensate for the ship's heading errors are sufficiently small to be considered adequate. Dynamic stability refers to the relationship between the rudder angle and the turning rate of the ship. Ships are defined to be dynamically stable when the spiral test, which determines the relation between the rudder angle and the steady rate of turning of the ship, gives a unique relationship between rudder angle and turning rate. Also, a vessel is considered dynamically stable if, when disturbed from straight motion by wave or other influences, it will resume the same path without any rudder corrections.

A ship which has excessive dynamic stability requires a large rudder force to achieve a given rate of turn. A ship with negative dynamic stability has a tendency to turn one way or the other when the rudder is held amidships. Comfortable ship handling usually requires a moderate amount of positive dynamic stability, and this can be designed without difficulty into cargo ships of conventional form. The very full forms of tankers are less easily endowed with positive dynamic stability; some of these ships have pronounced negative dynamic stability. Although large tankers exhibit negative dynamic stability, they do possess adequate directional stability. This is because the time involved in a turn or course deviation is large, allowing the helmsman or control system sufficient time to assess the situation and take appropriate corrective action. Compared to conventional cargo ships, large tankers move slowly, exhibiting somewhat of a slow motion effect in maneuvers.

Inadequate directional stability results in economic penalties due to increased voyage time and increased fuel consumption. This is caused by excessive amounts of rudder activity causing increased drag and increased power requirements. Therefore, vessel owners have economic incentives to ensure adequate course stability through design. Design factors which have a major effect on course keeping ability are vessel shape, length to beam ratio, rudder area, and steering control system response parameters.

COURSE CHANGING

Consideration must also be given to the ability to initiate a turn and to check or decrease it once it has started. This is referred to as course changing. This aspect of maneuvering is measured by a standard maneuver known as the zigzag or Z-Maneuver, which is illustrated in Figure 4 of Appendix A.

Vessel design factors which have a major influence on course changing ability are mass, length, hull form, rudder area, and rate of rudder movement. The ability to check a turn is defined by the overshoot angle. Reduction of the overshoot angle improves the course changing ability of a vessel. When a ship turns steadily and a counter rudder order is made, the rate of turn decreases eventually passing zero. The overshoot angle is the difference in heading between the moment of execution of counter rudder and the heading at the instant that the ship starts heading in the direction of the counter rudder order.

STOPPING

Unlike automobiles, ships have no brakes. The only ways to stop a moving ship other than letting it coast to a halt is by applying reverse thrust, increasing its drag, or by running into another object. The third means is most undesirable and is usually the event that maneuverability is intended to avoid.

Reverse thrust can be applied either with the ship's propeller or by external thrust mechanisms such as tugs. In any of those cases the energy available to reduce speed is generally much less than the energy available to propel the ship forward. The power of the astern engines, the design of the propeller, and the flow of water into the propeller all contribute to inefficiency in the astern mode.

The drag or resistance of a ship can be increased by disrupting the smooth flow pattern for which the hull was designed; this also increases the added mass of water carried along with the ship, effectively transferring energy and momentum from the ship to the water. Drag can be increased by using devices such as flaps or water parachutes, or through techniques such as cycling the rudder. Since resistance is proportional to the square of the vessel's speed, drag devices are not very effective at low speeds.

Large tankers are the most energy efficient means of transportation, requiring less than one percent the amount of energy necessary to move the same weight by automobile. Low resistance is the reason why a ship will advance a tremendous distance in coasting to a stop. The stopping ability of large tankers has received more attention in the press than any other aspect of maneuverability. An erroneous impression is often given that the ability of a tanker to avoid collision depends only on stopping ability. In addition, the distance required to stop a tanker is sometimes misreported. Despite reports to the contrary, the stopping ability of large tankers has never been the primary cause for any major CRG accident.

WAYS TO EVALUATE MANEUVERING, DEVICES, AND TECHNIQUES

The ways to test and evaluate maneuvering devices, as well as the maneuvering ability of the vessels themselves, can be discussed in three basic

modes: model scale, full scale, and computer simulation (mathematical modeling). Table 2 is a schematic of these modes and their subsets. Certain of these modes are more compatible with standard design procedures than are others.

Model Scale - This provides one of the least costly methods for testing a ship or device. Small scale models, though relatively less expensive, are subject to greater scale effects. Scale effects can be reduced somewhat by increasing the size of the model. Model testing is the method most commonly employed for maneuvering and control verification.

The use of large, manned models is primarily as a training tool. Many shipping companies send their captains to Port Revel at Grenoble, France, where there is an excellent ship maneuvering training facility. There the time relationships of maneuvering are not the same as for full size vessels, but considerable insight can be gained as to the effect of wind forces, anchors, turns in shallow water, and, to a certain extent, waves. The manned model affords the captain a latitude in control that can result in a beached model should his judgement be in error.

Full Scale - Builders trials are conducted on a new vessel to test the completed ship. The trials are used to measure many of the vessel's other characteristics, and sometimes they are used to measure maneuvering characteristics such as the turning circle, Z-Maneuver, and headreach in crash astern tests. If the vessel is the same as a previous vessel the trials are for verification. If the vessel is the first of a kind, the trials are more extensive in scope. Not only are these trials intended to verify the assembly of the vessel, but also to evaluate the design. Extensive acceptance trials were once performed on the lead vessel of each new Maritime Administration subsidized vessel. This is no longer the case however, and the extent of trials is left to the owner and the shipyard.

To produce meaningful results full scale maneuvering trials to evaluate complete maneuvering and control characteristics for a vessel must be carefully planned and conducted. These tests are expensive, and they are not conducted on a routine basis. The ESSO OSAKA report, Appendix A, illustrates the planning and coordination required for extensive trials. Other factors that affect the potential for successful data collection are the environment (winds, waves, and sea conditions) and loading of the vessel.

Another way to use full scale ships to evaluate maneuvering design changes is to evaluate them during normal operation. Ideally this evaluation would compare a class of vessels with and without a particular design feature. This method has the advantage of incorporating all the aspects of the waterway transportation system including the human element. It has the disadvantage of being extremely costly and time consuming and therefore has never been done as a controlled experiment. Investigations of vessel operations and accidents have been made for this study to compare motor propelled and steam propelled tankers. Detailed results are in Section IV.

Table 2

Methods for the Test and Evaluation of Maneuvering,
Devices, and Techniques

Verification of Physical Abilities	Verification of "System including" the Human Element
- Model Scale -	
Towing Tank Models	Larger Manned Models (*)
- Full Scale -	
Builder's or Special Trials	Operational Trials, with Environments (*)
	History of Operation (*) (steam/diesel) (*)
- Simulation (Mathematical Model) -	
Fast Time Analysis	Real Time Analysis; with Man and Simulated Environment (*)

(*) The operator, or human element can play a role in the outcome of the verification.

<u>Computer Simulations</u> - Also called mathematical modeling, simulations can be used as a passive or active means to evaluate maneuvering characteristics. A simulation can be relatively simple to model a simple system with few variables; or it can be extremely complex, involving almost all the parameters affecting shiphandling, including the interface with the ship operator.

Extensive mathematical modeling has been made possible in recent years through the development of large capacity high speed digital computers. The programs that are used to simulate ship maneuvering must be customized to represent individual ships. This involves gathering considerable information for use in the equations of motion. The information, referred to as hydrodynamic coefficients, is obtained from model tests of the vessel.

One of the major advantages of simulation is that the maneuverability of a ship can be assessed prior to construction of the vessel. Potential problems in maneuvering can be identified and corrected in the design stage. Alternative hull forms and various maneuvering devices can be evaluated to provide a design with satisfactory maneuvering characteristics. This aspect of design is increasingly gaining acceptance in the maritime community, for it is far easier to correct deficiencies in the design stage than to make extensive and costly modifications to a completed ship.

Many of the simulations of various vessels, maneuvering devices, and maneuvering techniques employed in this study omitted the effects of human judgement in the analysis. In order to accurately compare the effectiveness of the ships and devices, it was desirable to conduct identical simulations without including the human interface. In this way, the inherent maneuverability of a ship can be studied.

In actual shiphandling, the human factor is among the most important in maneuvering. An experienced and skillful operator can compensate for maneuvering shortcomings in his ship. Under proper control, two ships having widely differing maneuvering characteristics can be made to follow identical paths. Simulators that allow real time operator control can be most valuable in studying every aspect of maneuvering and maneuverability.

Real time simulators are useful for training ship operators as well as for research. The value of a simulator for both purposes increases with the sophistication of the device. The Computer Aided Operations Research Facility (CAORF) owned by and operated for the Maritime Administration is the most advanced ship simulator in the world.

CAORF uses a full scale bridge mock-up fitted with contemporary bridge controls. Numerous projections are used to create an image on a full panoramic screen in front of the bridge to realistically portray a harbor area with active shipping traffic underway. Numerous ships which can be individually controlled are simultaneously projected on the screen to simulate an active port. The operator must not only be aware of the operation and maneuverability of his own ship, but must remain aware of the activity around him. CAORF can also simulate night, fog and haze, wind, currents, and other factors affecting

ship maneuverability. Figure 5 portrays the CAORF system.

An advanced simulator can be used to evaluate situations which are either too dangerous or to expensive to evaluate using real ships and harbors. Factors affecting human judgement, such as fatigue, alcohol, experience level, and physical handicaps, can be studied in situations involving congested ship traffic in restricted waterways. Factors involving design of harbors, including location of channels, location of navigation aids, and siting of anchorage areas, can be analyzed with alternative designs at relatively little cost. And of course, basic training in shiphandling can be accomplished. As data from full scale ship maneuvering trials and comments from experienced ship operators are received, the simulator can be refined to provide even more accurate simulation.

Examples of various problems which have been addressed or have the potential for being addressed by real time simulation are:

* Analysis of situations in which ships are involved in collision or near misses.

* Analysis of causal factors leading to rammings and groundings.

* Evaluation of ship handling in routine and emergency situations.

* Evaluation of environmental constraints on maneuverability.

* Evaluation of ship bridge configurations and controls.

* Evaluation of harbor configurations and navigations aids.

* Development of criteria for training, retraining, and certification of ship's officers.

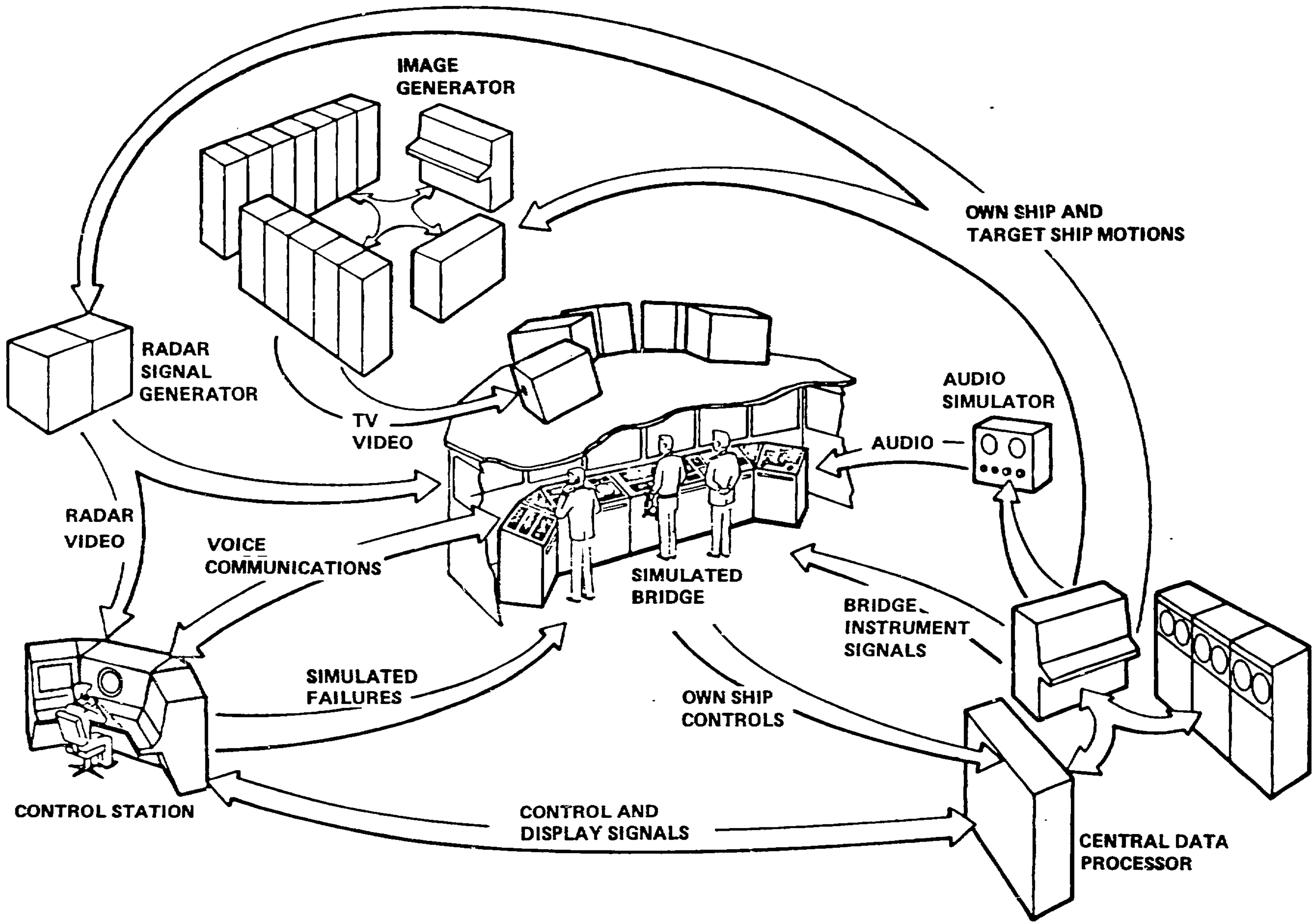


Figure 5 — Schematic Diagram of the CAORF Ship Simulator at King's Point, New York

Section IV
MANEUVERING AND STOPPING CAPABILITIES OF EXISTING TANKERS AND CARGO VESSELS

The maneuvering and stopping ability of vessels described in a general sense in the previous section are now examined in existing tank ships and cargo vessels. The record of CRG accidents is also examined to evaluate the role, if any, of maneuverability in such accidents. The purpose of these examinations is twofold: first, to establish a baseline of large tanker maneuvering against which improvements from devices and techniques can be compared; and second, to compare the maneuvering ability of large tankers with that of smaller tankers and cargo vessels. The information for this examination was drawn from mathematical simulation studies and from full scale trials. One set of trials, those of the 278,000 DWT ESSO OSAKA, contains much useful information on large tanker maneuvering in both deep and shallow water. For this reason the main body of the ESSO OSAKA report is attached as Appendix A. Maneuvering and stopping capabilities in this section are organized according to turning, stopping, course changing, and course keeping. Following this examination the section concludes with a discussion of the accident history of large tankers from 1969 through 1977.

TURNING

Turning of tank vessels as a function of size was examined by comparing the turning capabilities of five tankships ranging in size from 37,000 DWT to 322,000 DWT. Table 3 lists the principal characteristics for these vessels. The information for the four smallest tank ships is representative for vessels of that tonnage, while the information for the 322,000 DWT tank vessel is from published trials of the twin screw tank vessel ARTEAGA. The total population of vessels in each size group will have somewhat different physical characteristics and, of course, maneuvering characteristics. This comment also applies to the three cargo vessels selected from the available full scale maneuvering data. The principle characteristics of the cargo ships are provided in Table 4.

The maneuvering simulation model and associated hydrodynamic coefficients was purchased by the Coast Guard from Stevens Institute of Technology, which has been associated with vessel maneuvering analysis for many years. The coefficients and, to a certain extent, the simulated maneuvers have been compared by Stevens personnel to available full scale trials data. They have concluded that the coefficients lead to proper simulation of full scale maneuvers.

Full scale trials data has been used primarily because few cargo vessels have been model tested to determine maneuvering coefficients. Prior to the late 1960's the Maritime Administration (MarAd) required that subsidized vessels have full scale maneuvering trials for the first vessel of a class.

Table 3

Principal Characteristics of Tank Vessels
for Simulation of Turning Maneuvers and Stopping Computations

	Tanker Size (Deadweight Tons)				
	37,000	80,000	165,000	280,000	322,000
Length Between Perpendiculars, m (ft)	182.0 (597)	232.6 (763)	290. (951)	325. (1066)	330. (1083)
Beam, m (ft)	27.4 (90)	38.1 (125)	47.4 (155)	53.0 (174)	53.3 (175)
Draft, m (ft)	11.3 (36.9)	12.2 (39.9)	16.0 (52.3)	22.1 (72.3)	24.8 (81.4)
Displacement, Long Tons	43,820	87,130	179,070	318,985	375,120
Block Coefficient	0.77	0.80	0.81	0.83	0.85
L/B	6.63	6.10	6.12	6.13	6.19
B/T	2.44	3.13	2.97	2.40	2.15
$\frac{\text{Rudder Area}}{\text{Length X Draft}}$	0.018	0.017	0.015	0.017	0.019

Table 4

Principal Characteristics of Merchant (Cargo) Vessels for Full Load and Trials Conditions

Length Between Perpendiculars in m (ft)	143.3 (470)	177.6 (582.5)	204.2 (670)
Beam, m (ft)	21.0(69)	25.0(82)	25.9(85)
Draft, m (ft)	9.0	10.7	9.8
Displacement, Long tons	16,870	31,995	32,565
Block Coefficient	0.62	0.67	0.63
L/B	6.81	7.10	7.88
B/T	2.34	2.34	3.06
$\frac{\text{Rudder Area}}{\text{Length X Draft}}$	0.018	0.015	0.016
Trials Conditions:			
Draft, m	-	5.9	5.6
Displacement, Long Tons	-	15,800	16,000

Full scale trials data is sometimes difficult to use, because of the varying environmental conditions that exist. There is however, a high degree of confidence in the use of full scale data.

Figures 6 and 7 are turning circle trajectories for the tanker series and the cargo vessels, respectively. The figures are dimensional, with the horizontal axis representing the advance, or how far the vessel moves in the direction in which it was originally headed. Side reach is the distance off the original track line. The trajectory is plotted at the ship's center of gravity. In a deep water turn there is a rather large drift angle associated with the tank ship. This is shown schematically in Figure 4. The swept path, if plotted, would be greater than the center of gravity trajectories. To examine one aspect of the turning ability of tankers, maximum advance is plotted in Figure 8. This shows that the advance does not increase linearly with vessel size. For example, the increase in advance between an 80,000 DWT and a 160,000 DWT vessel is only 130 meters, or a 17 percent increase in advance for a 100 per cent increase in cargo carrying capacity. The curve is steeper at the lower deadweight tonnages. Such relationships are sometimes referred to as economies of scale and are applicable to the economics of most forms of transportation.

It is common practice to relate dimensional results (feet, meters, etc.) to a physical dimension under study to make the results non-dimensional. Advance is non-dimensionalized using the vessel length as a standard. Dimensionless results for advance are given in the following table:

	Length, meters	Advance, meters	Advance/Length
37,000 DWT	182.	580.	3.2
80,000 DWT	232.	740.	3.2
165,000 DWT	290.	900.	3.1
280,000 DWT	325.	1040.	3.2
322,000 DWT	330.	1220.	3.7

These results show that each tank vessel, when given hard over (35 degrees) rudder at full speed will advance no further than four ship lengths. For all but the largest of the five vessels, the advance is just over three ship lengths.

Figure 7 is a plot of turn trajectories for three cargo vessels. The characteristics of these three vessels, are presented in Table 4. The important information from the figure is as follows:

Length, meters	Advance, meters	Advance/Length
143.3	560.	3.9
177.6	720.	4.1
204.2	1010.	4.7

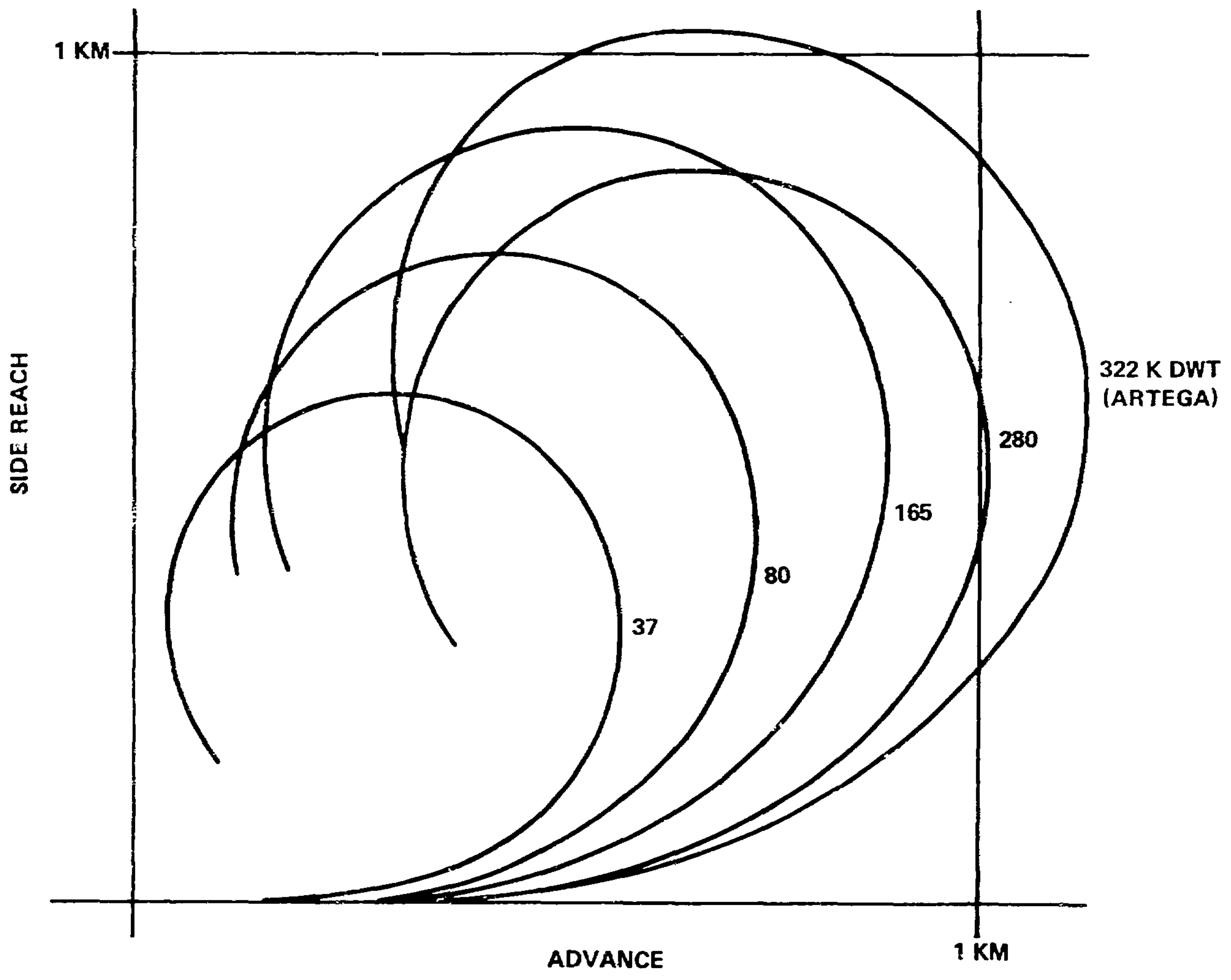


Figure 6 — Turning Ability for Tank Vessels from 16 knot Approach Speed in Deep Water

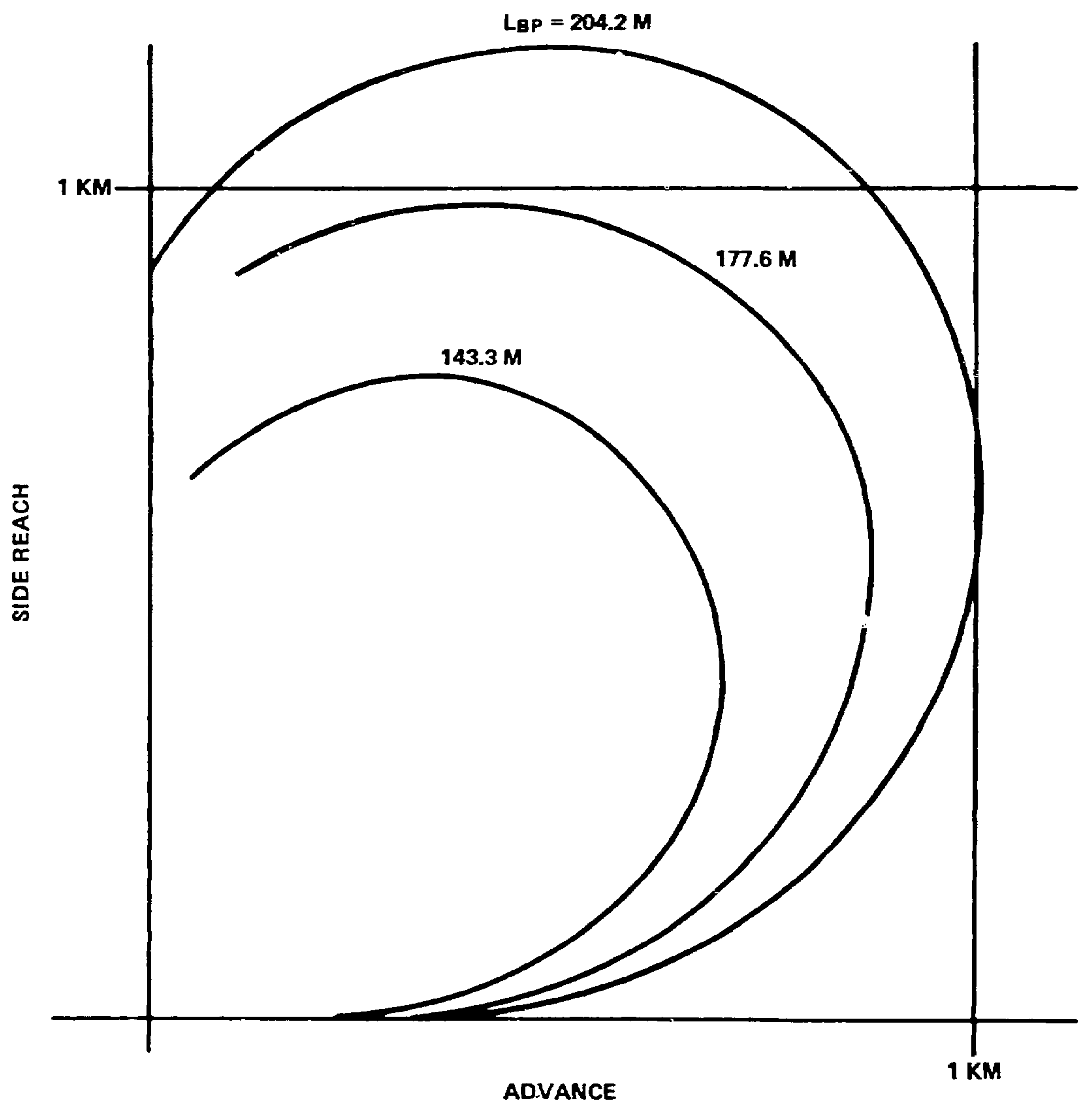


Figure 7 — Turning Ability for Merchant Vessels from 20 knot Approach Speed in Deep Water

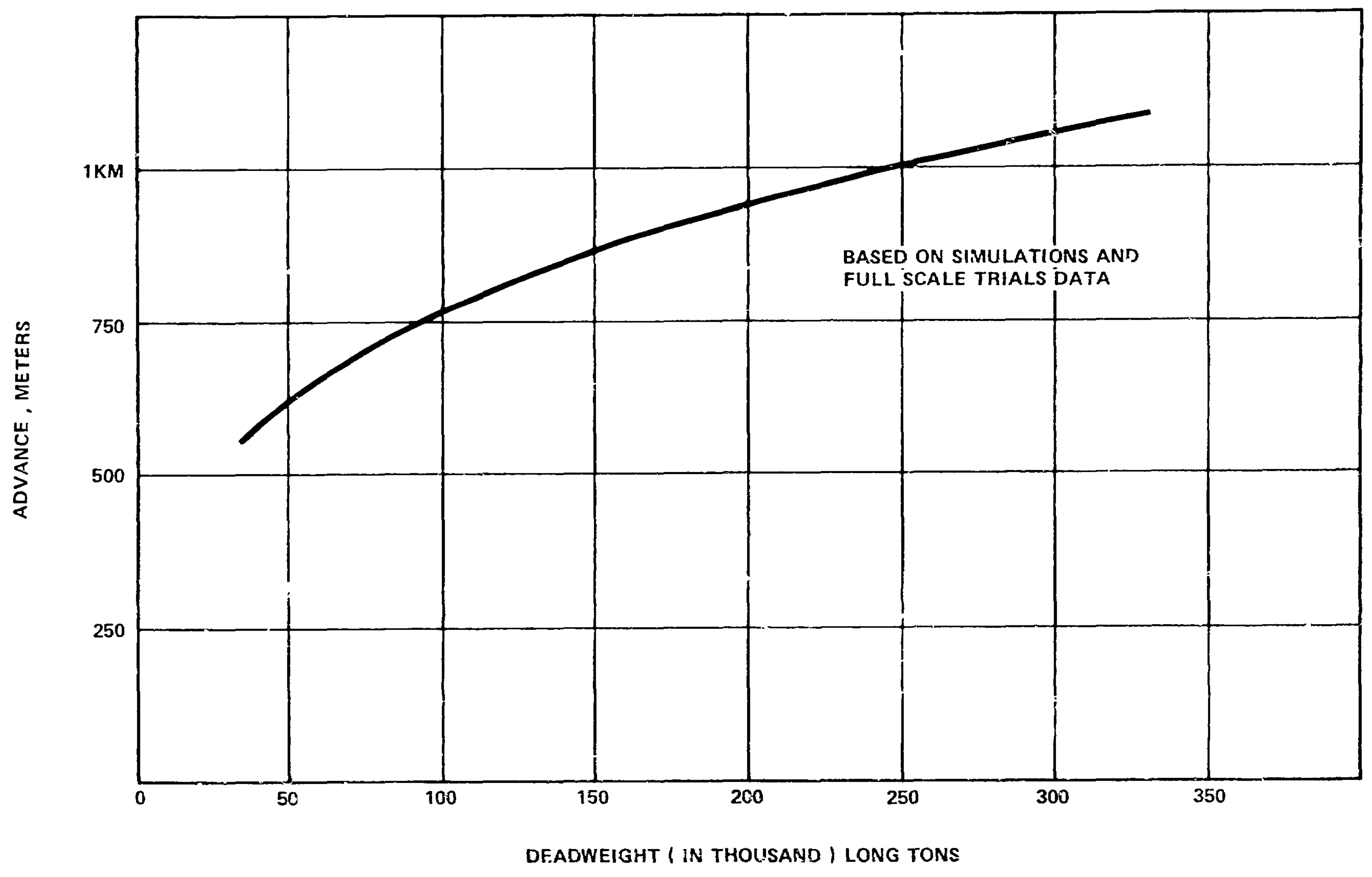


Figure 8 - Maximum Advance from Turning Maneuver for Tank Vessels in Deep Water

The cargo vessels turn with a maximum advance from four to five times their length. This means that a cargo ship has more dynamic stability than a tanker and will not make a turn as well as a tanker.

This nature is seen in Figure 9, which is a plot of rudder angle on the horizontal scale and ship length/turning radius (L/R) on the vertical scale. Turning ability increases with increasing values of L/R. For example:

(1) for two ships of the same length, the one that turns better will be able to turn in a smaller radius, thus making L/R a greater valve.

(2) for a vessel that turns in the same circle (or radius), but is shorter than the other will have a smaller valve of L/R. This can be seen for the 177.6 meter cargo vessel compared to the 165,000 DWT tanker:

	177.6 m Cargo Vessel	165,000 DWT Tanker
Length, meters	177.6	290.
Turning Radius, meters	406.0	371.
Turning Ability (*)	0.44	0.78

* Ship Length/Turn radius

The conclusion from the above example and Figure 9 is that a tanker which carries 165,000 long tons of cargo has a greater turning ability than a cargo vessel that carries only 19,000 long tons of cargo, and it requires approximately the same radius to turn. These are representative results that are further illustrated by the areas shown in the figure. In summary the relative turning ability of tank vessels, expressed in terms of L/R, does not vary appreciably with vessel size and is generally better than that of cargo vessels for the same rudder angle.

The turning capabilities discussed above are for maximum approach speed and hard over rudder angles. The ESSO OSAKA trials confirm that approach speed does not significantly affect turning radius. Table 3 of Appendix A lists the maximum swept advance of 1160 meters or 3.5 ship lengths for 35 degree rudder angle with an approach speed of 7 knots. The simulation with an approach speed of 16 knots indicated an advance of 3.2 ship lengths. Considering that the simulation gives the path of the center of gravity of the tankers and not the maximum swept path, the advances compare very favorably. Further, trial results of ESSO OSAKA's conventional turn from different approach speeds confirms that turning ability of tankers is not dependent on approach speed. Tables 7 and 8 and the associated text in Appendix A discuss this further.

In addition to this conventional method of measuring the turning ability of a ship, other methods have been proposed. Two of these are the coasting turn and the accelerating turn. The coasting turn is similar to a conventional turning maneuver except that the engine is ordered stopped at the instant the initial rudder execute command is given. The accelerating turn begins with the

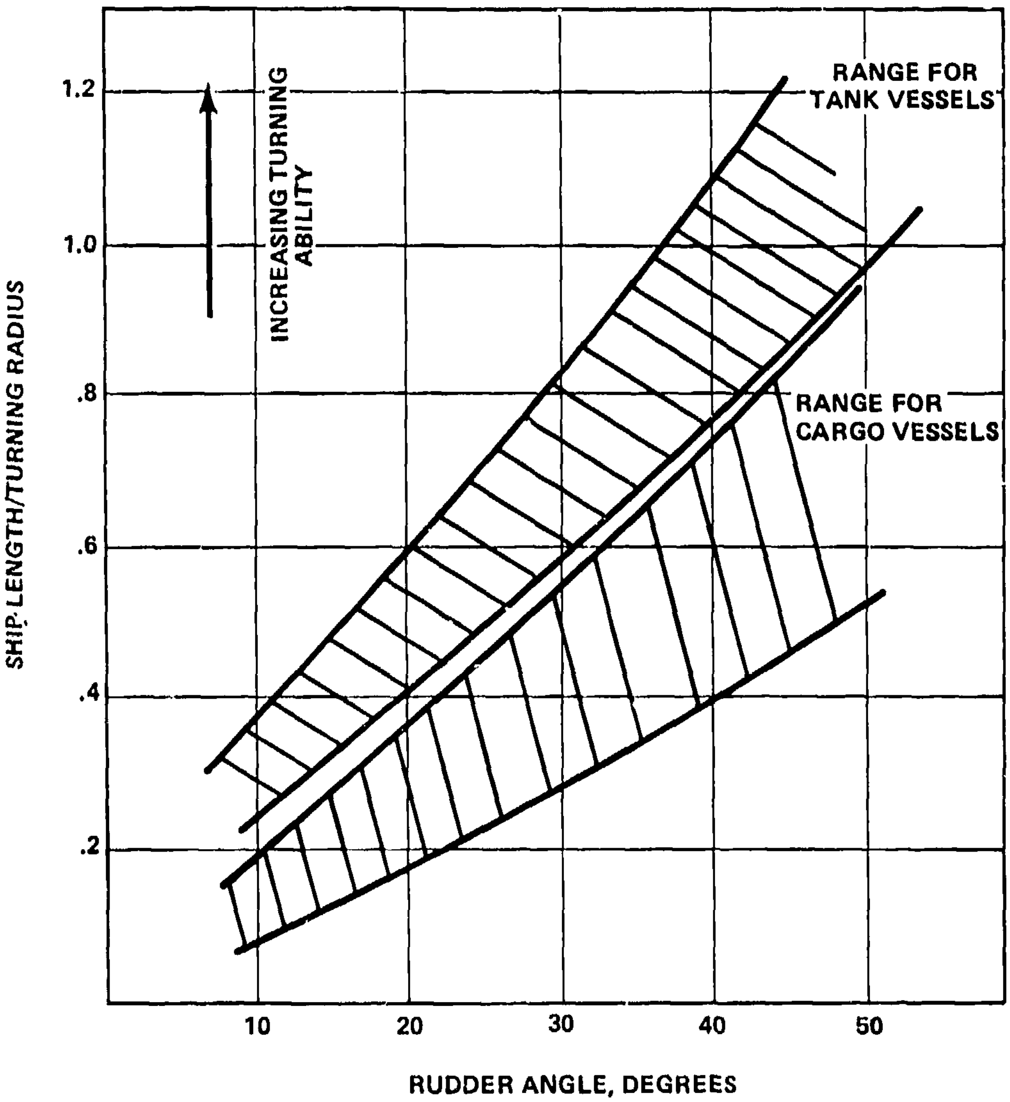


Figure 9 – Turning Ability for a Range of Tank Ships and Cargo Vessels

ship dead in the water or travelling ahead at a very slow speed. The rudder is put over hard and the engine is simultaneously ordered to a prescribed RPM. Both of these turns were part of the ESSO OSAKA trials. Figure 7 of Appendix A gives the results for the coasting turn and Figure 8 gives the results for the accelerating turn. These figures show the effect of water depth on the maneuvers. Also comparison of these maneuvers with each other and with the conventional turn shows the effect of RPM on the turning circle. Such comparisons are shown in Figures 14 and 15 of Appendix A. The discussion of these results from the report is very informative:

> "The accelerating turns made in the medium and shallow water depths confirm facts well known to shiphandlers, i.e. that advance and tactical diameter can be reduced by 'kicking ahead' with the propeller in a slow speed turn. The reason is that water flow past the rudder is quickly increased, while the hull hydrodynamics forces aiding or resisting the turn are not.
>
> "On the other hand, the coasting turns showed a directionally predictable decrease in turning ability when the propeller discharge flow was removed from the rudder. Much of the rudder was then put in a separated flow region behind the idling propeller. But perhaps of greatest significance is that the single screw VLCC, one predicted to be virtually unmanageable in slow speed maneuvers, was able to turn reliably at slow speeds, even with the engine stopped."

STOPPING

Before discussing the stopping ability of existing large tank vessels, some mention must be made of the measure of stopping ability, the crash astern maneuver. Unlike the turning maneuver, the crash astern maneuver, or crash stop, is not used at service speeds. The reason is that during the crash astern maneuver, the ship has an unpredictable trajectory from the desired track with a loss of directional control. Unlike the turning circle which is a highly controlled maneuver, the crash astern is uncontrolled. All single screw ships, not just tank vessels, behave this way during a crash stop maneuver. At moderate and low speeds, less than 8 knots, the crash stop maneuver results in less deviation from the desired straight track and is more useful. Therefore, while stopping on a straight path by continuous application of astern power is only realistic at moderate speeds, comparisons of the stopping maneuver can still be made using the conservative assumption that they stop in a straight line. In this examination both calculated and measured stopping distances are used. Because of the nature of the crash astern maneuver, the full scale trial results of stopping distance, ahead reach, will be less than those calculated for straight line stopping. In making comparisons this should be remembered.

Stopping of tank vessels as a function of size was examined by comparing

the stopping ability of the same five tankers used in the turning comparisons. The stopping ability of the four smallest tankers was calculated and that for the 322,000 DWT tanker was taken from trial results. Calculations of the straight line stopping distance were based on the formulation for stopping presented by Clarke and Wellman (1972) which has been validated by full scale trials.

The variables in this formulation are displacement, initial speed, propeller diameter, available astern horsepower, and time to reverse the engines. Table 5 provides the characteristics needed to calculate the stopping ability of the tankers . Two important factors in determining stopping distance are initial speed and available astern horsepower.

All the vessels considered are steam propelled with standard ahead and astern turbine installation. For this calculation the maximum astern horsepower available was assumed to be 40 percent of the maximum ahead horsepower. This corresponds to approximately 50 percent of ahead RPM. The maximum ahead speed for the four smallest tankers is in the 15 to 16 knot range, so 15.5 knots was used for ahead speed in the calculations. The 322,000 DWT tanker has a maximum speed of approximately 14.5 knots, and the crash astern trials for this ship were conducted at an initial speed of 14.2 knots. While the initial speed for the four smallest and largest tankers are not the same, the speeds used in the comparison represent approximately the same percent of maximum ahead speed.

Table 5 shows the results of the stopping comparison. The stopping ability, in vessel lengths, ranges from 11.4 ship lengths (2070 meters) for the small tanker to 15.3 ship lengths (4990 meters) for the 280,000 DWT tanker. This is a 34 percent increase proportional to vessel's length, and a 140 percent increase in total stopping distance. In addition to this comparison, the comprehensive work by Crane (1973) provides excellent information on stopping ability as a function of tank vessel size. Of particular interest in that paper is the comparison between a 1950 vintage tanker, the 27,000 DWT ESSO SUEZ, and a 1968 vintage tanker, the 191,000 DWT ESSO MALASIA. The paper states:

> "These two vessels represent the major size increase of tankers occuring between 1950 and 1968 which caused an increase in stopping headreach of about 160 percent at all speeds. In terms of ship lengths this amounts to an increase of about 55-60 percent."

Stopping ability of tank vessels compared to cargo vessels was examined for the five tank vessels with the three cargo vessels used in the turning

Table 5 -

Stopping Ability of Various Sizes of Tank Vessels
from an Approach Speed of 15.5 knots

Tank Vessel Deadweight	Length Meters	Displacement Long tons	Propeller Diameter Meters	Maximum Ahead	HP Astern	Stopping Distance Meters	Distance/ Length
37,000	182	43,820	5.8	15,000	6000	2070	11.4
80,000	232.6	87,130	7.0	22,000	8800	2925	12.6
165,000	290.	179,070	7.9	26,700	10680	3955	13.6
280,000	325	318,985	9.1	36,000	14400	4985	15.3
322,000 (*)	330	375,120	2 (7.2)	36,000	14400	4330	13.1

*Based on Results of Full Scale Trials and an approach speed of 14.2 knots.

comparison. The results from full scale trials for these three cargo vessels are:

Length, meters	Initial Speed	Stopping Distance, meters	Distance/ Length
143.3	18.3	1120	7.8
177.6	23	1300	7.3
204.2	25	1700	8.3

The comparison between this information and Table 5 is straightforward. The 280,000 DWT tanker requires approximately four times the stopping distance of a 178 meter cargo vessel, which is about twice the distance per unit length.

This information places the question of stopping ability of large tankers in perspective. They do not have the same stopping ability as smaller vessels, but neither do they require 15 miles to stop as was recently reported in an article and an editorial of the Washington Post. The following is a quote from the July 23, 1979, issue of the Washington Post.

> "approach 18 to 20 knots .... You must fully understand the momentum of a vessel of that tonnage.... At that speed it would require 15 miles to stop".

This quotation was attributed to the Deputy Commissioner of Customs for Trinidad and Tobago, Victor Cockburn. Mr. Cockburn is referring to two tank ships, the 270,000 DWT ATLANTIC EMPRESS and the 210,000 DWT AEGEAN CAPTAIN, that collided on July 19, 1979. As can be seen in the figures, 15 miles is not correct, but between 14,000 and 16,000 feet, or three miles is correct.

COURSE CHANGING/TURN CHECKING ABILITY

To examine the course changing/turn checking ability of large tankers, results of zigzag tests (Z-Maneuver) are compared. Although the turning circle and the crash stop are direct measures of the maneuvering ability that they measure, the Z-Maneuver does not relate as directly. While this test has been widely used to investigate the ability of a ship to initiate a turn and to check a turn, it is more difficult to grasp the physical meaning of the maneuver. For this examination of course changing ability for various size tankers and cargo ships, the first overshoot angle of the 20-20 Z-Maneuver, as defined in Appendix A, is used. The larger the angle the more difficulty a ship will have in starting to turn and in pulling out of a turn. The time for the first overshoot is also recorded for comparative purposes.

To examine the effect of tanker size on course changing ability, the five tankers that were used in the turning and stopping analysis are compared. Again the information for the smallest four tankers was taken from mathematical simulations, and the large tanker results are from full scale trials. The

results of the examination are shown below:

	Initial Speed, knots	First Overshoot Angle	Time to First Overshoot, Seconds
37,000 DWT	16	15.4	77
80,000 DWT	16	16.1	106
165,000 DWT	16	17.9	134
280,000 DWT	16	13.9	143
322,000 DWT	14.5	15.0	163

These results show that the overshoot angle does not vary with the size of the tanker, and that the course changing ability of tankers is not affected by size. However, the smaller tankers respond more quickly (time to overshoot) to rudder commands than larger tankers.

In comparing tankers and cargo ships the following full scale trial results from the three cargo ships previously reported were used:

Cargo Vessel Length (m)	Initial Speed, Knots	First Overshoot Angle	Time to First Overshoot, Seconds
143.3	18.3	8	46
177.6	22.8	10	45
204.2	24.8	8	55

Comparing these results with those for tankers shows that the smaller cargo ships have better course changing ability and that they respond more quickly to rudder commands than tankers. Again the difference is less than a factor of two.

A measure of a large tanker's ability to continue maneuvering without propulsion power is shown by the coasting Z-Maneuver. This maneuver is similar to the conventional Z-Maneuver except that the engine is ordered stopped at the instant the first rudder execute command is given. The Z-Maneuver is continued until the ship's heading no longer responds to rudder commands.

The standard and coasting Z-Maneuver were part of the ESSO OSAKA trials. Results are shown in Figures 11, 12, 16, 17 and 18 of Appendix A. One surprizing result from these trials was the ability of the ship to maneuver at low speeds. The report states:

> "The coasting Z-Maneuver gave further evidence that the trial vessel could maneuver reliably and predictably with engine stopped, even at speeds as low as 1.4 knots. In all cases it appeared that the ship was still responding to rudder commands when the maneuver was terminated."

COURSE KEEPING ABILITY

Examination of the course keeping ability of various size tank vessels and cargo ships is difficult because there is no single measure which can be used for comparison. In Section III the distinction between a directionally stable and dynamically stable ship was made. From a hydrodynamic consideration the dynamic stability of a ship can be measured by the spiral maneuver or the modified spiral maneuver.

The procedure to conduct a spiral maneuver or "Dieudonne spiral" and a discussion of the meaning of the results is contained in Gertler and Gover's 1959 paper. In that test, a steady propeller speed is set and the throttle settings are not changed during the maneuver. A straight course is obtained and the rudder is deflected to about 15 degrees right and held until the rate of change of heading remains constant. The rudder angle is then decreased incrementally and held until the rate of change of heading again remains constant. This procedure is repeated until the rudder has covered a range of from 15 degrees on one side to 15 degrees on the other side and back to 20 degrees on the first side. The paper states:

> "The numerical measures obtained from the spiral maneuver are the steady rates of change of heading versus rudder angles. A plot of these variables is indicative of the inherent characteristics of the ship. If the plot is a single continuous curve going from right rudder to left rudder, as shown in (Figure 10(a)), the ship is said to be dynamically stable. If, however, the plot consists of two branches joined together to form a 'hysteresis' loop, as shown in (Figure 10(b)), the ship is said to be dynamically unstable. In addition, the size of the loop (height and width) can be used as a numerical measure of the degree of instability; the larger the loop, the more unstable the ship. The width of the loop is also a fairly direct indication of probable course keeping ability since it defines the envelope of rudder angles which must be employed to keep the ship from swinging from port to starboard."

Unfortunately this maneuver is not readily applicable to large tankers because of the time it takes to conduct and because it does not account for active steering. As stated in Appendix A.

> "Spiral test results provide certain technical information on steady state turning characteristics at small fixed rudder angles; in the absence of active steering. However, they provide no direct information on maneuvering or course keeping ability with active steering; at least not in the case of large slow vessels such as VLCC's. In fact, spiral tests are not meaningful to the ship handler, especially as they apply to VLCC's, unless unusual results are obtained

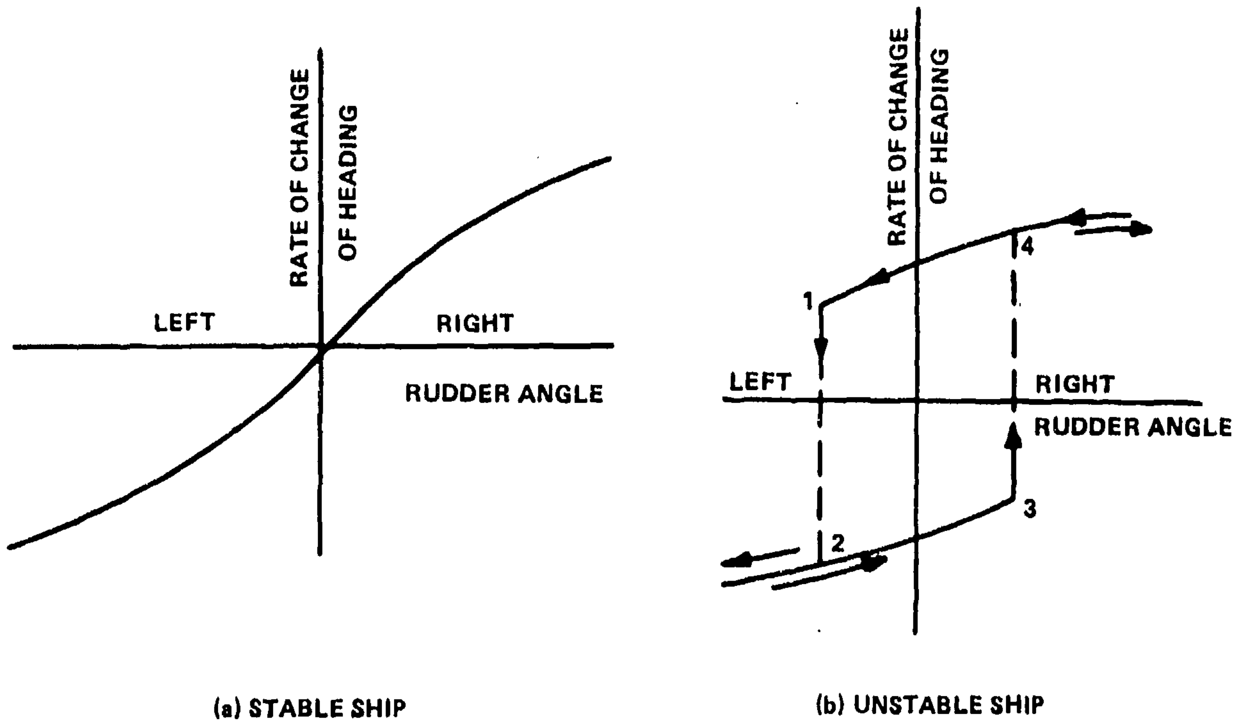


Figure 10 — Typical Curves from Spiral Maneuvers

from the Z-Maneuver, such as abnormally large overshoots."

There are no spiral test results for the ships compared in this study. However, most full form ships like tankers are dynamically unstable. The five tankers compared here all have negative dynamic stability. Most finer hulled ships are dynamically stable; the three cargo ships probably have positive dynamic stability. Therefore, while quantitative comparisons cannot be made, it can be qualitatively stated that cargo ships have better course keeping ability than tankers and that the course keeping ability within the range of tankers didn't vary appreciably with size. This is supported by the track keeping results obtained from the Puget Sound study performed for the Coast Guard. This study concluded that tank vessels between 80,000 DWT and 400,000 DWT held track equally well.

ACCIDENTS

Since the overall objective of this study is to avoid collision, ramming, and grounding accidents of tank vessels as a means of reducing oil pollution, a discussion of accidents is necessary. CRG accidents involving large tank vessels (over 100,000 DWT) were investigated.

Information on collision, ramming, and grounding accidents involving tank vessels greater than 100,000 DWT was extracted from Lloyds Weekly Casualty reports and other sources for the nine year period from January 1, 1969, through December 31, 1977. This data base includes accidents to tankers and combination carriers carrying oil. The investigation also includes a compilation of the world operating tanker fleet population greater than 100,000 DWT for the same time period.

Many studies of tanker accidents and resulting polluting outflows have been made. The effort in this study does not duplicate those but instead looks at the overall accident rate, analyzing it by vessel size and type of propulsion. Accident rate is the number of CRG accidents divided by the number of tankers operating over a time period. Table 6 is the population of tank vessels greater than 100,000 DWT from January 1969 to January 1978. The population after January 1975 was adjusted to account for tankers in a laid-up status. Prior to January 1975 the number of laid-up tankers over 100,000 DWT was so small that it did not have an impact on the total operating population. Figure 11 shows that the operating population of tank vessels greater than 100,000 DWT has grown from 131 in January 1969 to 1163 in January 1978.

The table below summarizes the accidents the large tank vessels were involved in during the period and compares them by vessel size and type of propulsion. Figure 12 lists the number of accidents which occured each year. The accident rate (accidents per tankers operating per year) for large tank vessels by year is shown in Figure 13. This figure shows that the accident rate for tank vessels has steadily decreased since 1969, and in 1977 it was at its lowest, .031 tanker accidents per operating year. Another way of looking at this is that if the 1977 accident rate remained steady, one could expect a

Table 6 - 1969-1977 Population of Tank Vessels Greater Than 100,000 DWT - Adjusted For Tankers in Lay up after Jan. 1975

	100,000-149,999		150,000-199,999		200,000-249,999		250,000 and up	
	Steam	Motor	Steam	Motor	Steam	Motor	Steam	Motor
Jan 69	43	51	18	1	14	2	2	0
Jan 70	46	62	24	9	41	2	10	0
Jan 71	55	77	29	12	103	2	17	3
Jan 72	56	104	34	17	157	7	33	4
Jan 73	68	119	51	27	207	9	65	5
Jan 74	75	147	62	33	244	16	116	12
Jan 75	80	195	66	39	279	18	196	15
Jan 76	75	216	58	40	255	18	246	16
Jan 77	77	265	59	69	292	20	324	22
Jan 78	72	279	54	79	299	23	333	24

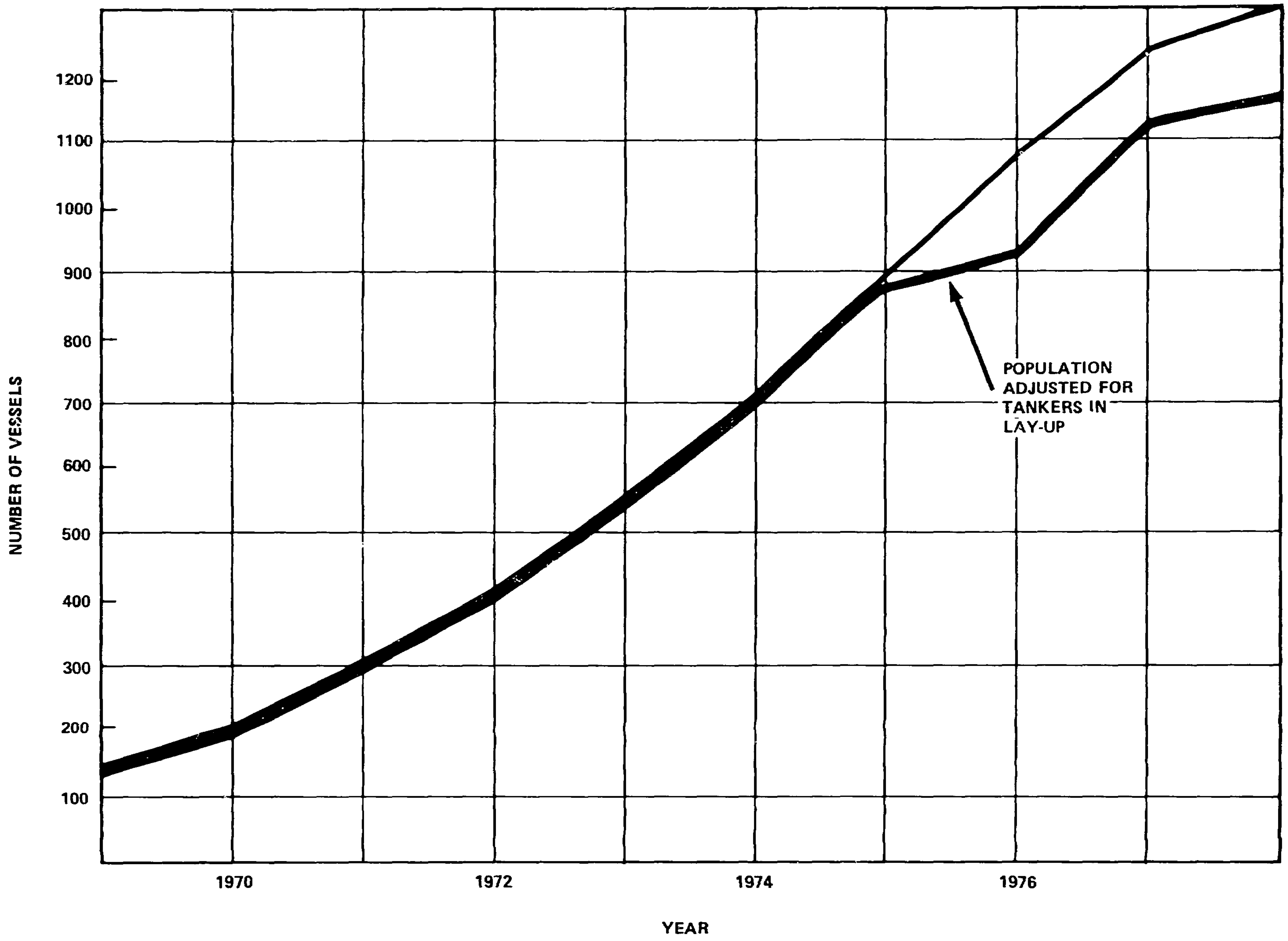


Figure 11 - Population of Tank Vessels Larger than 100,000 DWT for the Years 1969 through 1978, Including Adjustment for Lay-Up

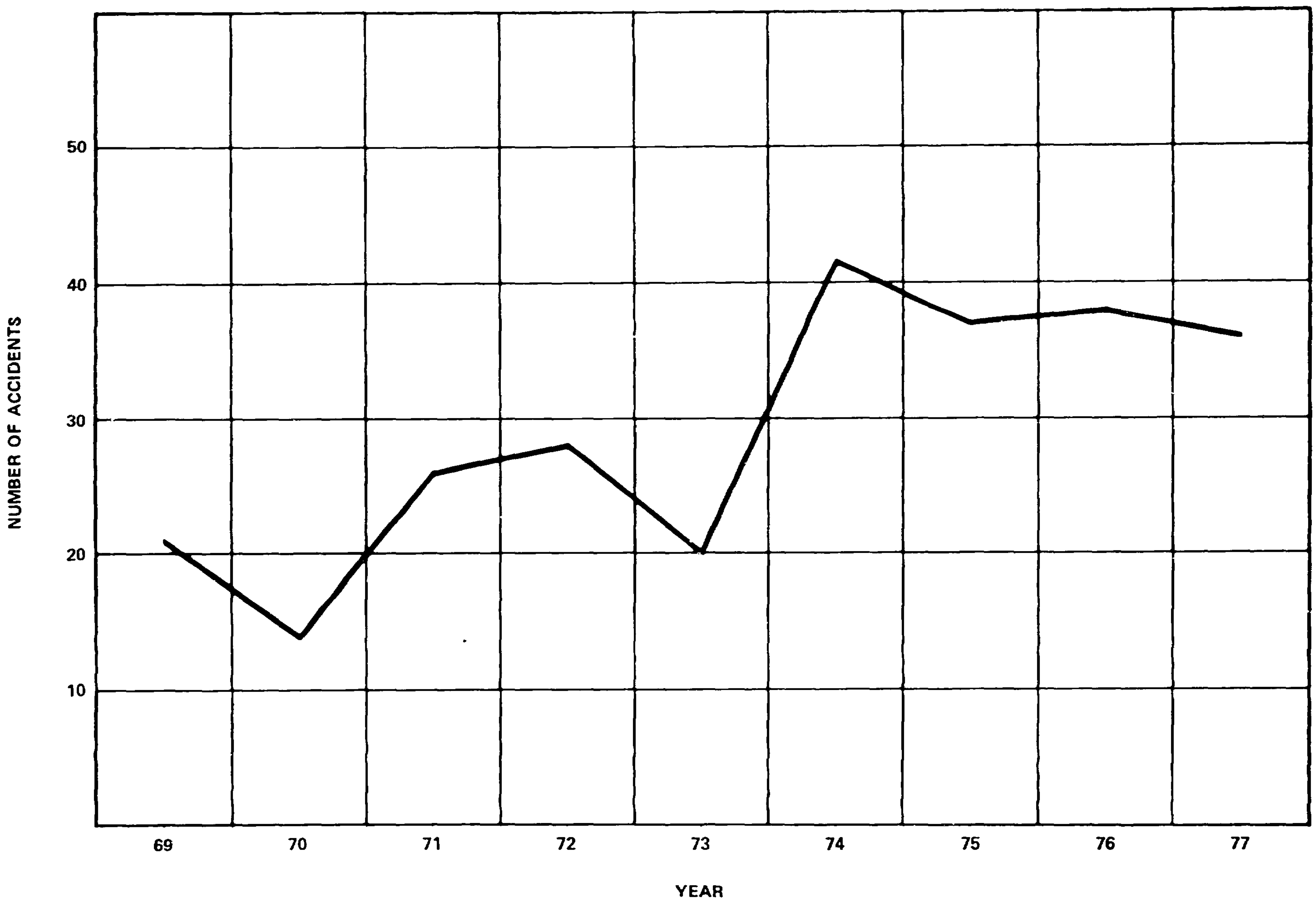


Figure 12 - Accidents of Tank Vessels Larger than 100,000 DWT for the Years 1969 through 1977

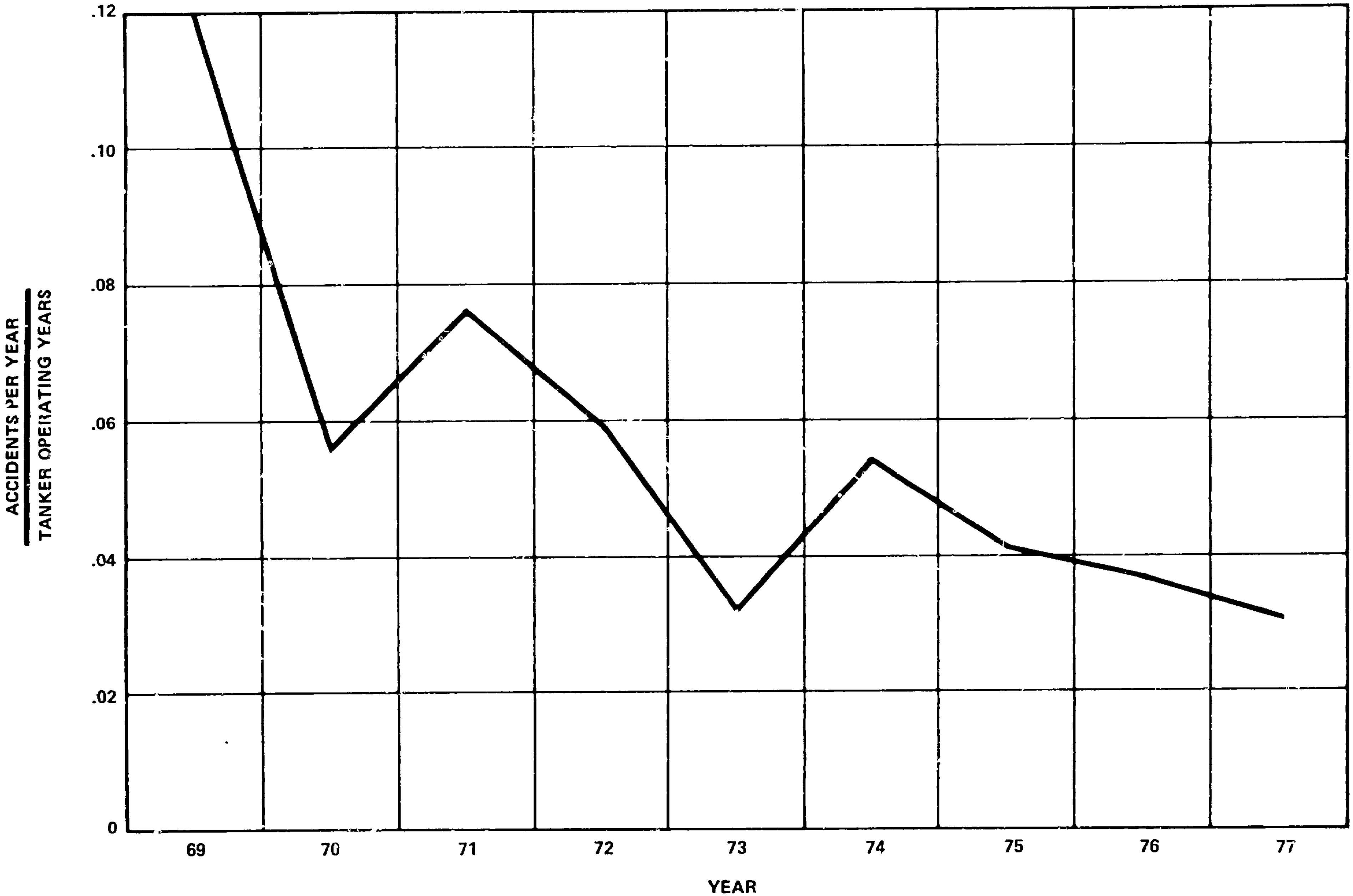


Figure 13 - Accident Rate of Tank Vessels Larger than 100,000 DWT for the Years 1969 through 1977

large tanker to have a CRG related accident only once every 32 years.

	Steam Propelled	Motor Propelled	Total
100-150,000 DWT	37	60	97
150-200,000 DWT	20	13	33
200-250,000 DWT	92	3	95
250,000 and above	38	1	39
Totals:	187	77	264

SUMMARY OF EXISTING SHIPS

In comparing a typical large tanker of approximately 250,000 DWT with a much smaller tanker of 40,000 DWT it is seen that on a non-dimensional basis turning, course keeping, and course changing abilities are comparable while the stopping distance proportional to length of the large tanker is about twice that of the smaller tanker. Similar comparisons, again on a non-dimensional basis, with cargo ships have shown that large tankers turn better, do not have quite as good course changing/course keeping ability, and have about half the stopping ability. Therefore while the maneuvering ability of large tank vessels has been somewhat maligned, they are comparable to smaller tankers and many cargo ships with the exception of ability to stop from full speed. In stopping, large tankers are not 10 to 20 times as "bad" as smaller tankers or cargo ships, but really only about half as good. Additionally, large tankers have some maneuvering capabilities that small ships do not have. Due to their large mass, when the engine is "kicked ahead" (increasing the propeller RPM and rate of flow over the rudder) rudder effectiveness and turning ability are increased without appreciably increasing the vessel's speed. Smaller vessels do not have this luxury. Not to lose sight of the goal to reduce CRG accidents, it is interesting that the worldwide accident rate for large tankers has been decreasing.

Section V
MANEUVERING DEVICES

GENERAL DISCUSSION

The technical literature is filled with proposals for devices and ideas to improve the maneuvering ability of vessels. Most were proposed before the advent of large tankers. Some of the devices which show the greatest promise have been installed and evaluated on ships. The term "promise" represents a subjective evaluation of the various devices: an assessment of the cost, reliability, and operability of each device compared to its effectiveness. By using such subjective measures and service experience the list of potential devices was reduced, and then each device was subjected to a computer analysis.

An extensive listing of the devices is presented in Table 7. The table provides a breakdown to categorize the devices and an indication of their "promise" to improving maneuverability of large tankships. The devices have been sorted into five categories:

* rudder augmentation
* propulsion augmentation
* propeller/rudder augmentation
* thrusting devices
* drag augmentation devices

Each of these devices, whether it has been used on a vessel or not, represents an addition to the ship. It requires additional design effort and increases both the initial and operating costs of the vessel. Operational techniques and methods, also listed in Table 7, do not require any design or construction changes. They can be used at the discretion of the vessel's master.

Some of the devices listed in Table 7 do not improve the maneuvering ability of large tankers, or provide only marginal improvements at high cost. Therefore each device has been ranked on the basis of three subjective parameters: improvement in maneuverability, cost, and reliability. The end result of this filtering process, illustrated in Figure 14, is to eliminate from further detailed study those devices that are ineffective or impractical. There was an additional filter subsequently applied to further gage the effectiveness of the devices: mathematical simulations of six devices on a large (280,000 DWT) tank ship.

Table 8 shows the three performance indices for the devices that augment the rudder. The fourth column in the table indicates whether the devices have

Table 7

Devices and Operational Techniques to Improve the Maneuvering and Stopping Ability of Vessels

Rudder Augmentation

Increased Rudder Area
Increased Rudder Angle
Increased Rudder Rate
Twin Rudders
Schilling Rudder
Flapped Rudder
Steerable Flapped Rudder
Active Rudder
Shutter Rudder
Rotating Cylinder Rudder
Rotating Cylinder with Flap
Kitchen Rudder
Clam Shell Rudder
Jet Flap (Fluidic)
Bow Rudder

Propulsion Augmentation

Twin Screw (and Rudder)
Increased Astern Power
Controllable Pitch Propeller
Contra-Rotating Propeller

Propulsion/Rudder Augmentation

Steerable (Kort) Nozzle
Voith Scheider (Vertical Axis)
Steerable Propeller

Thrusting Devices

Fixed (bow,stern) Thruster
Trainable Thruster
Jet Engine Thruster
Rockets

Drag Augmentation Devices

Stern Anchor
Stern Flap (behind screw)
Twin (splayed) Rudders
Brake Flaps
Bow Opening
Parachute

Operational Techniques and Methods

Slower Approach Speed
Hard-over Turn
Propeller Kick
Rudder Cycling
Tug Assistance:
- Rudder Tug
- Braking Tug
- Alongside Tug

Traditional Tug

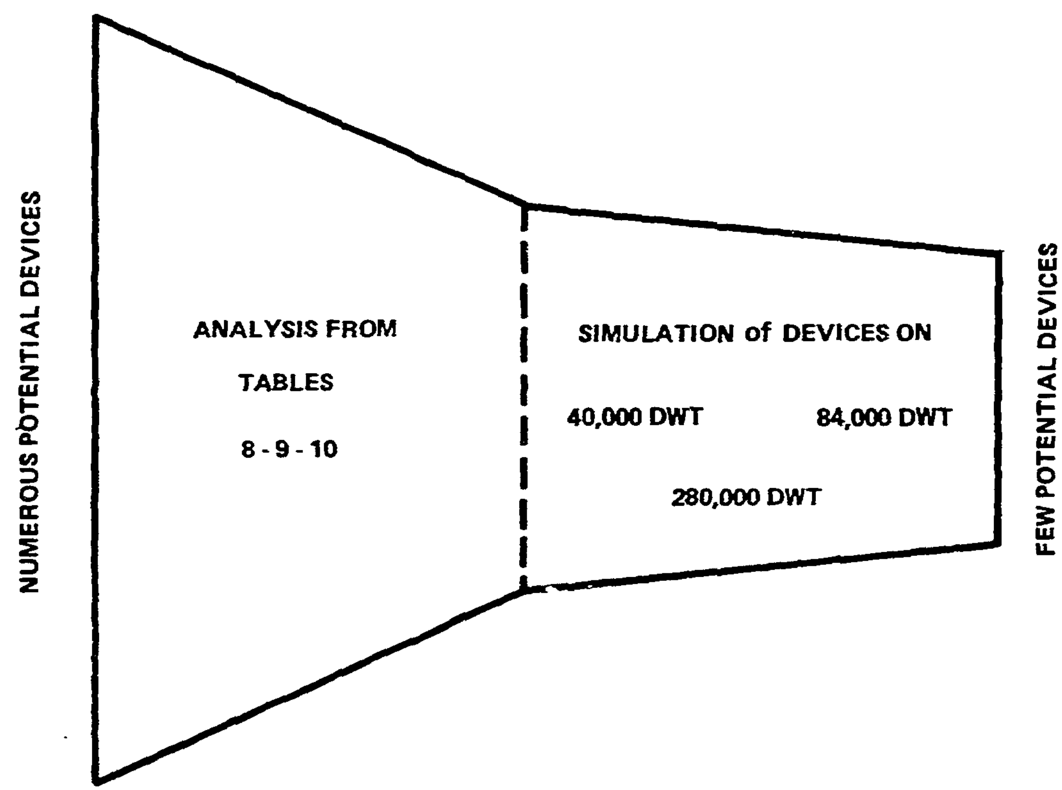


Figure 14 — The Filtering of the Devices to Improve the Maneuvering and Stopping Ability of Large Tank Vessels Through Analysis and Mathematical Simulation

Table 8

Performance Indices for Devices
to Improve Maneuverability and Controllability
by Augmentation of Rudder Effectiveness

	Maneuver-ability	Cost, Design	Relia-bility	on large tankers
Increased Rudder Area	B	A	A	A
Increased Rudder Angle	B	B	A	A
Increased Rudder Rate	C	A	A	A
Twin Rudders	B	C	B	B
Shilling Rudder	B	A	A	C
Flapped Rudder	C	B	B	C
Steerable Flapped Rudder	C	C	B	C
Active Rudder	B	C	C	B
Shutter Rudder	A	B	A	C
Rotating Cylinder Rudder	A	C	C	C
Rotating Cylinder w/Flap	A	C	C	C
Kitchen Rudder	A	C	C	C
Clam Shell Rudder	A	C	C	C
Jet Flap (Fluidic)	C	C	B	C
Bow Rudder	C	C	C	C

Index	Improvement in Maneuverability	Cost, Effect on Vessel Design	Practicality Reliability	Device installed on Large tankers
A	Significant	Insignificant	High	Yes, Operational
B	Moderate	Moderate	Moderate	Yes, Experimental
C	Slight	Significant	Low	No

been used on large tankers. The indices and how they are applied are as follows:

* The degree of improvement in maneuverability and controllability of each device; "A" means a significant improvement.

* The cost for implementing the device on the the vessel; "A" means the device has an insignificant effect on the cost.

* The reliability of the device and its entire components; "A" means that the device has high reliability and practicality.

Similar compilation and subjective evaluations for propulsion and propulsion/rudder augmentation devices are shown in Table 9. Thrust and drag augmentation devices are in Table 10.

Devices that scored an "A" or "B" for improved maneuverability are examined further. These devices are described, including a photograph or drawing if available. Most of the devices in the photographs (primarily from publications of the Royal Institution of Naval Architects) have been used on small ships, tugs, or fishing vessels. Those devices analyzed using mathematical simulation are presented in greater detail later in the report, and are summarized below with devices that scored an "A" or "B" in the evaluation.

<u>Increased Rudder Area</u> - Increased rudder area generally increases the turning ability and the course changing ability of a vessel. Only limited increases in rudder area can be achieved because of geometric constraints associated with the rudder/propeller system, Figure 15. Increasing the area by making the rudder deeper is effective from a hydrodynamic aspect, but not practical due to drydocking and channel depth restrictions. A longer rudder suffers from increased bearing and strength problems plus decreased hydrodynamic efficiency because of its shape. Extensive study of this device requires much model testing and is not considered particularly promising.

<u>Increased Rudder Angle</u> - An angle of 35 degrees is the practical limit that rudders remain an effective turning device. Some large tankers have a maximum angle of 40 to 45 degrees, which improves the turning and course changing ability at low (maneuvering) speeds. Increased rudder angle may require major configuration changes to the stern, and would require artificial means to modify the flow in order to retain effective rudder forces. Rotating cylinders, discussed below, have been proposed to modify the flow over the rudder, but they have high costs and low reliability. Further study of this device is not considered necessary.

<u>Schilling Rudder</u> - Figure 16 shows a Schilling rudder, which is like a conventional rudder except for the flared trailing edge. This modified shape is designed to make the rudder more effective than normally expected for its size. The concept attempts to achieve improvements similar to increased rudder area. It also has similar problems. The device has been installed on small

Table 9

Performance Indices for Devices
to Improve Maneuverability and Controllability
by Augmentation of the Propulsion and Propulsion/Rudder Systems

	Maneuver-ability	Cost, Design	Relia-bility	on Large Tankers
Propulsion Augmentation				
Twin Screw (and Rudder)	B	C	A	A
Increased Astern Power	B	B	A	A
Controllable Pitch	B	B	B	B
Contra-Rotating Propellers	C	C	B	C
Propulsion/Rudder/Augmentation				
Steerable (Kort) Nozzle	A	B	B	B
Vertical Axis Propulsor	B	B	B	C
Steerable Propeller	B	C	C	C

Index	Improvement in Maneuverability	Cost, Effect on Vessel Design	Practicality Reliability	Device installed on Large tankers
A	Significant	Insignificant	High	Yes, Operational
B	Moderate	Moderate	Moderate	Yes, Experimental
C	Slight	Significant	Low	No

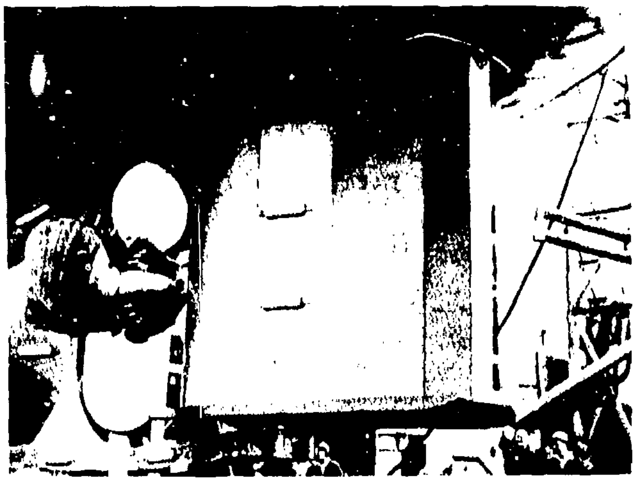
Table 10

Performance Indices for Devices
to Improve Maneuverability and Controllability
by Thrust and Drag Augmentation

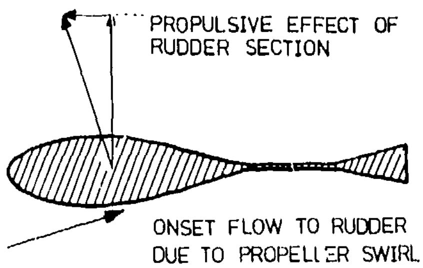
	Maneuver-ability	Cost, Design	Relia-bility	on Large Tankers
Thrusting Devices				
Fixed (Bow, Stern) Thrusters	B	B	A	A
Trainable Thruster	C	B	B	C
Jet Engines Thruster	C	C	C	C
Rockets	C	C	C	C
Drag Augmentation Devices				
Stern Anchor	B	C	B	C
Stern Flap (behind screw)	C	C	C	C
Twin (Splayed) Rudders	C	A	B	C
Brake Flaps	C	B	B	C
Bow Opening	C	C	B	C
Parachute	C	A	B	C

Index	Improvement in Maneuverability	Cost, Effect on Vessel Design	Practicality Reliability	Device installed on Large tankers
A	Significant	Insignificant	High	Yes, Operational
B	Moderate	Moderate	Moderate	Yes, Experimental
C	Slight	Significant	Low	No

Figure 15 - Rudder and Propeller from a 356,000 DWT Tankship
(Note the man standing under the rudder.)



(a) The coastal tanker *Bromley,* showing Schilling rudder installation.



(b) Schilling rudder and propeller interaction.

Figure 16 - Shilling Rudder shown on a 1000 DWT coastal tanker.

coastal vessels of the 1000 DWT size range and has performed satisfactorily. No further study of this device for large tank vessels was made.

Active Rudder - An active rudder has a submerged motor and propeller as an integral part of the trailing edge of the standard rudder, as shown in Figure 17. The additional flow created by the propeller increases the rudder effectiveness, especially at slow speeds, when flow velocity over the rudder is low. The device is ranked as costly and having low reliability, but it is examined further mainly for potential application to smaller tankers. As with the other devices to augment rudder effectiveness, the active rudder increases the turning and course changing ability of a vessel.

Shutter Rudder - This device consists of three or more rudders which are mechanically linked and is shown in Figure 18. It has been adapted to tugs and work boats that are equipped with ducted propellers. The main advantage is in utilizing the optimum amount of the propeller race. This is another device that is not considered further because of the impracticalities of adaptation to large tankers. It may be used on small tankers.

Rotating Cylinder Rudder (also with Flap) - This device, shown fitted to a model (Figure 19) at the National Maritime Institute in England is designed to provide high lift and large rudder forces. Due to the increase in turning and course changing ability claimed for this device, further study has been carried out. Application to large tankers is remote due to high cost and low reliability. Another proposed device adopts this rudder with a trailing edge flap, which provides even greater turning ability. Complexity, reduced reliability, and great costs make further study unwarranted.

Kitchen Rudder - This device is similar to the thrust reversing device on jet aircraft, but it is conceptually more complex. The concept is intended to provide ahead and astern thrust depending on the position of the reverser. Neither the problems associated with the structural design, nor the operational complexity of this concept have been adequately studied. The rudder system must be capable of absorbing upwards of 50,000 horsepower in a hard-over turn. For these reasons the concept was not considered in this study. Due to its potential application to smaller ships, it was examined in simulation efforts sponsored by the Maritime Administration . The Clam Shell device has a similar configuration with the same structural problems, and it is not studied further.

Twin Screws and Rudders - A moderate increase in maneuvering ability is anticipated for this device. The use of twin screws and rudders can improve stopping ability, and differential thrust between the two propellers improves course changing and turning ability. Increased maneuverability when docking or navigating in close quarters is an obvious advantage. This also provides increased reliability of the propulsion and steering systems as a whole through duplication. Lower propulsion efficiency and the stern hull form make this an extremely costly device, with high initial and operating costs. Unlike the majority of devices in Table 7, this one has been used on large tankers, so further study to quantify the improvements in maneuvering is warranted.

Figure 17 - The Pleuger active rudder in tandem behind the main propeller.

Figure 18 - A Shutter Rudder installation on the 40m tug *Salimi.*

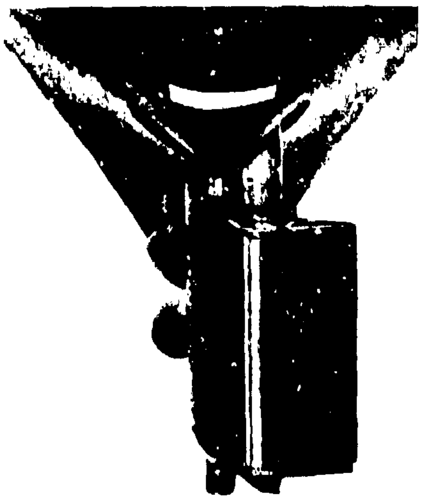


Figure 19 - The rotating cylinder flap rudder on an NMI Model.

Increased Astern Power - Increased astern power calls for increasing the output of the astern turbine in a steam propulsion plant. The designer can add more stages to the astern section or increase the steam flow through the astern nozzles. The primary effect on maneuverability is increased astern horsepower. This device is studied further, including an analysis of operating experience. Compared to steam powered ships, diesel vessels have increased astern power. The degree of astern power is limited to 80 percent of the ahead power because of the considerably lower propeller efficiency in reverse.

Steerable Kort Nozzle - A steerable Kort nozzle is shown installed on a 25,000 DWT Great Lakes bulk carrier, Figure 20. The large ring serves as a device to direct the flow from the propeller. This device has a limited maximum rudder angle. Most installations of a steerable Kort nozzle have increased the propulsive efficiency, reducing the operating costs somewhat. As can be seen from the indices in Table 9 this device is in development and could eventually be applied to large tank vessels. This device is studied further.

Steerable Propeller - This device is similar to an outboard motor that can be rotated through 360 degrees. The propeller unit is rotated to direct the thrust. Figure 21 shows one installed on a harbor tugboat. Both this and the Voith-Schneider (vertical axis) units can only be used on tugs, ferries and small coastal vessels because of power limitations. No further study is conducted.

Voith-Schnieder (vertical axis) Propulsion - The vertical axis propulsor shown in Figure 22 and the steerable propeller can provide thrust in any direction and are used without a rudder. The Voith-Schneider has been successfully installed on tugs, workboats, and the Staten Island Ferries under construction. This device is not examined further for large tankers because of power limitations.

Tunnel Thruster - The tunnel thruster has been installed on the largest tankers for use in maneuvering around docks, buoys, and to offshore mooring systems. They are ducts that have an impeller in the middle, and they are installed transversely in the ends of the vessel to provide the greatest amount of turning force. Thrusters are not effective above forward speeds of 2 to 4 knots. They are most effective at zero speed, which is when the rudder is completely ineffective. This device is studied in more detail.

Stern Anchor - The stern anchors that are currently being installed on tankers and bulk carriers are designed to prevent a vessel from swinging within a channel or confined area. Employing a stern anchor as a device to reduce stopping distance requires extensive redesign of the anchor handling equipment. This may be practical for small tankers. It is not considered further for application to large tankers because suitable machinery is beyond the present technology. Since it may be a viable device for small tankers, it is examined in the simulation study.

Drag Augmentation Devices - Although these devices are not considered further, Figure 23 showing three drag augmenting devices is of interest. The

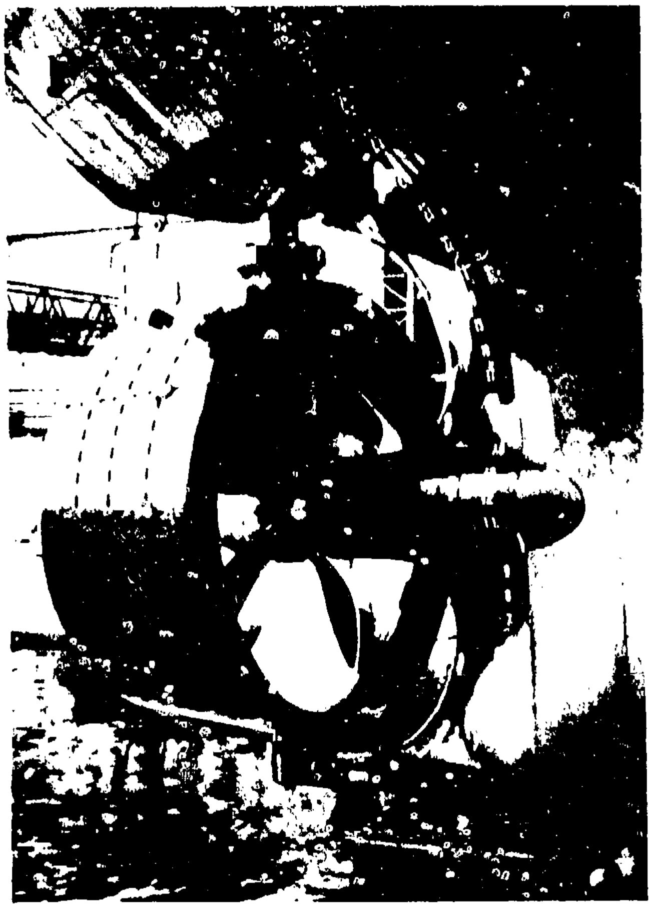


Figure 20 - Bulk carrier *Ralph Misener,* (25,000 DWT) with Steerable Kort Nozzle.

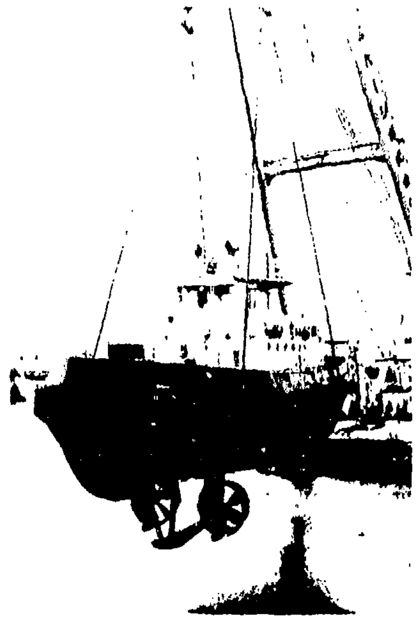


Figure 21 - Steerable Propeller on the tug *Al Alliah.*

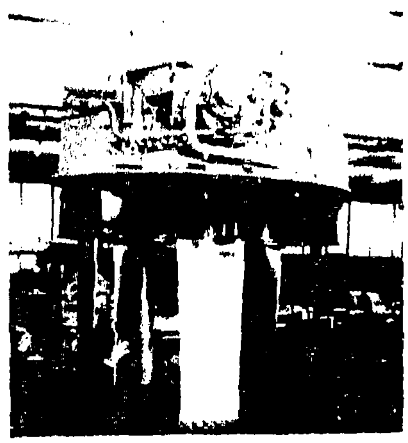
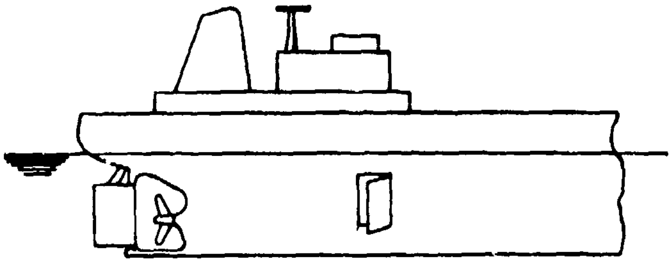
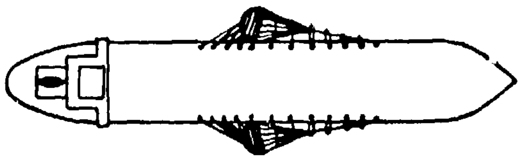


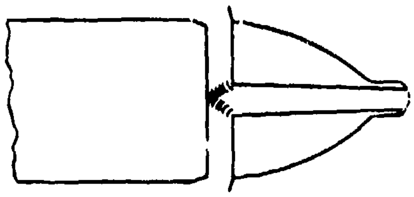
Figure 22 - A Voith-Schneider unit with blades 1.6m long.



(a) POSITION OF BRAKE FLAPS AT STERN OF TANKER



(b) POSITION OF PARACHUTES ON SIDE OF TANKER



(c) POSITION OF DUCTS IN BOW OF TANKER

Figure 23 – Schematic Views of the Three Braking Devices

splayed rudder device is somewhat similar to braking flaps. It requires a control system modification to a twin rudder vessel to simultaneously provide full right rudder on the starboard rudder and full left on the port rudder. These devices provide only slight improvements in stopping ability and are not considered further.

In this discussion and Tables 8 through 10 most of the devices were found to be impractical for large tankers. The following devices are studied further using a simulation model:

* Active Rudder
* Twin Screw and Twin Rudder
* Increased Astern Power
* Steerable Kort Nozzle
* Tunnel Thruster
* Stern Anchor (for smaller tankers)

The concepts of increased rudder area and increased rudder angle are important but require extensive model tests. Of the two, increased rudder area does not appear particularly promising, but a detailed study of rudder and hull interaction needs to be conducted to answer the increased area question.

DETAILS OF THE VESSEL AND DEVICES APPLIED TO THE EXPANDED MARITIME ADMINISTRATION FULL FORM HULL CONFIGURATION

The initial study using mathematical simulations of maneuvering devices was performed by Hydronautics, Inc., for the Maritime Administration. This study began in 1978 with emphasis on expanding the hydrodynamic coefficients for the low L/B (length divided by beam) hull forms to include twin screw and twin rudder configurations. These full forms were developed and tested in shallow water since full form hulls are much wider and shallower than conventional tanker hull forms. The purpose was to seek an efficient hull form for the shallow harbors and waterways of the United States.

The study obtained hydrodynamic coefficients for a Maritime Administration Standard series full form bulk carrier modified with a twin screw, twin rudder configuration. With this information the survey of maneuvering devices could include a twin screw configuration. The selection of devices for this study was based primarily on the potential effect on an 84,000 DWT tanker and are listed below:

* Twin Propellers and Rudders
* Increased Astern Power

* Stern Anchor

* Maneuvering Propulsion Devices including:
  Tunnel Thruster
  Active Rudder

* High Lift Rudders including:
  Flapped Rudder
  Rotating Cylinder Rudder

* Thrust Vectoring Devices including:
  Steering Kort Nozzle
  Kitchen Rudder

Although the details of this study are in a later section, a summary of the Hydronautics findings is appropriate. These results pertain to vessels of the 84,000 DWT size:

* generally the baseline vessel (84,000 DWT without devices) was able to maneuver nearly as well as with devices.

* twin screw, twin rudder configuration provides only marginal improvement in the ability to maneuver.

* the stern anchor shows considerable promise to improve stopping ability.

* the best performer was the steerable Kort nozzle.

* some of the highly mechanical devices showed significant improvements in maneuverability.

The Coast Guard added to the Maritime Administration effort on the 84,000 DWT tanker by sponsoring mathematical simulation studies of 40,000 DWT and 280,000 DWT tankers. In this study the same full hull form was used. To obtain maneuvering data for a larger and a smaller vessel the geometric characteristics of the 84,000 DWT vessel were scaled appropriately. This scaling procedure is commonly used in model testing. The characteristics of the three tankers are shown in Table 11.

This hull form is considered reasonable for the study of a large tanker since its proportions are suitable for a design intended to carry maximum deadweight in restricted water depths. This size was selected since it represents the size of new tankers which may be constructed for service to U. S. ports which, in general, have relatively shallow water.

Recent articles in the maritime press have reported that many companies have ordered 80,000 DWT vessels to satisfy pollution requirements of the 1978 Port and Tanker Safety Act. Some companies have sold large vessels and purchased 80,000 DWT vessels in their place. H. P. Drewry, a compiler of

Table 11

Principal Characteristics of Three Tank Vessels
Used for Maneuvering Devices Simulation Study
(Based on MarAd Standard Series)

	40,000 DWT	84,000 DWT	280,000 DWT
Length Between Perpendiculars in m (ft)	160.9 (527.9)	206.1 (675.9)	307.9 (1009.9)
Beam, m (ft)	32.2 (105.6)	41.2 (135.2)	61.6 (201.9)
Draft, m (ft)	10.7 (35.2)	13.7 (45.1)	20.5 (67.3)
Displacement, Long tons	47,600.	100,000.	333,300.
Block Coefficient	0.85	0.85	0.85
L/B	5.0	5.0	5.0
B/T	3.0	3.0	3.0
Rudder Area, Movable in m (ft)	57.4 (617.9)	94.2 (1013.)	210.2 (2261.)
$\frac{\text{Rudder Area}}{\text{Length X Draft}}$	0.033	0.033	0.033

statistical data on the world's tankship fleets, has reported a tanker boom on the horizon:

> "The recent boom in orders for tankers of about 80,000 DWT has provided much welcome relief to a few shipyards and the market in general. It appears that both owners and charterers alike are looking on this size of tanker as the optimum size for profitable tanker operations in the 1980's..... These new generation tankers are specially designed for shallow draught operations in restricted areas, such as the U. S. Gulf and U. S. East Coast."

The 40,000 DWT tanker is representative of a size common to U. S. coastwise trade; it carries out numerous delivery chores and amounts to 24 percent of the U. S. flag tankship fleet. The 280,000 DWT tankship on the other hand, represents one of the largest size vessels that trades in the U. S. Eleven vessels in the 200,000 DWT and above range have been constructed at U. S. shipyards, with the largest (390,000 DWT) delivered in 1979. There are presently few harbors or ports that can accept a vessel of this size, even if it has a shallow draft configuration.

The selection of concepts for simulation is based on the evaluation in Tables 8 through 10. The concepts selected are based on potential application to a large (280,000 DWT) tanker, and include concepts simulated for the 84,000 DWT tanker in the initial Maritime Administration study. Certain maneuvers do not provide any information on some devices as the following matrix shows:

Concept	Turning Circle	Accelerg Turn	Crash Stop	Stopping Maneuver	20-20 Z-Maneuver
Basic Ship	Yes	Yes	Yes	Yes	Yes
Twin Screw/Rudder	Yes	Yes	Yes	Yes	Yes
Increased Astern	-	-	Yes	Yes	-
Stern Anchor (*)	-	-	Yes	Yes	-
Tunnel Thruster	Yes	Yes	-	-	Yes
Active Rudder	Yes	Yes	-	-	Yes
Kort Nozzle	Yes	Yes	Yes	Yes	Yes

* Applicable to smaller tankships only.

The simulations are for an approach speed of 8 knots for all maneuvers, except the accelerating turn, which starts at slow speed. All maneuvers were in shallow water with a water depth to tanker draft ratio (D/T) of 1.2. Examination of devices in shallow water conditions provides conservative answers compared to the deep water conditions of Section IV. It also represents the most common environment for ship maneuvering: confined and congested coastal waters and harbors.

Details relating to hydrodynamic performance and mathematical modeling of the concepts may be found in the Hydronautics report. In selecting size or

number of units for the various maneuvering devices, the following items were emphasized: realistic dimensions, locations, and capabililties for each device, and design and arrangement in accordance with manufacturer's specifications.

The costs were obtained from the Maritime Administration, and are reflective of the costs that would be charged by U. S. shipyards for incorporating the device into new construction. They are current costs based on completion of the vessel before the end of 1981. The costs are for different tankers than those used in the simulation analysis, but they are representative and are referred to as follows:

MarAd Tanker Designation	Deadweight Long tons	Initial Costs
T6	37,000	$49,100,000
T8	91,800	$69,000,000
T10	265,000	$136,900,000

Twin Rudders/Twin Propellers - The concept was investigated in great detail. Planar motion mechanism tests were carried out to obtain hydrodynamic coefficients for the mathematical simulation model.

A short feasibility study was carried out to define the twin screw configuration. The study concluded that twin screw machinery could fit within a conventional single screw hull, and that propellers turning outboard over the top and a centerline skeg with open shaft and strut arrangement should be used. Propeller diameter was based on expected propulsion coefficients. The overall maneuverability performance of twin screws and rudders is slightly better than the conventional single rudder and propeller arrangement. This concept suffers from higher initial and operating costs. The twin screw configuration requires 25 per cent more power for a nominal 16 knot speed; the horsepower requirements and costs for new construction are:

	Horsepower		
	Single	Twin	Cost
40,000 DWT	11,050	14,430	$3,510,000
84,000 DWT	18,140	23,500	$4,700,000
280,000 DWT	40,000	51,600	$6,400,000

Optimizing the hull configuration may provide better powering relative to the single screw baseline, but further research and development is required.

Increased Astern Horsepower - Increased astern power reduces stopping time and distance. In typical steam turbine plants, the astern turbine is capable of generating about 40 percent of ahead power.

There are basically two methods which can be used to increase astern power. In the first, the turbine efficiency is improved by providing more stages or higher speeds. Besides an increase in turbine size and costs, there

is another disadvantage: when the turbine runs ahead, friction and eddying gases in the astern stages cause losses which detract from the ahead efficiency. In the second method, increased astern power can be obtained by simply increasing steam flow without changing either the number of stages or the blade speed. Studies indicate that the astern steam flow could be increased to 150 percent of the rated full power ahead throttle flow without affecting the size of the turbine. Furthermore, various combinations of the two methods are possible. The second method was used in the simulations. It is estimated that the capital cost of new construction and retrofit would be:

Tanker	New	Retrofit
T6	$410,000	$5,850,000
T8	$410,000	$8,190,000
T10	$410,000	$11,700,000

One method for evaluating maneuvering devices is to check the operations of one class of vessels with the device in comparison to those without the device. To perform such experiments, conditions must be closely controlled. Unfortunately, no such experiments have been performed in this field. However, in a sense there is one device which is installed on a significant number of tank vessels which are motor propelled - that of increased astern horsepower compared to steam ships. Because of their design, large motor propelled tankers have approximately 80 percent of ahead power available astern compared to 40 percent for steam tankers. In comparing the operating experience of steam versus motor propelled tankers, accident rates were compared. Table 12 shows accident rate broken down by vessel size. The same information is shown graphically in Figure 24. This shows that motor propelled tankships and steam propelled tankships have approximately the same accident rate when considered over the whole deadweight range: .048 steam tankers as compared to .042 for motor tankers. Table 12 indicates that increased astern horsepower may reduce CRG accidents for tankers under 150,000 DWT, but there are so many other factors involved in tanker accidents that such a conclusion cannot be drawn with certainty. The number of accidents for motor propelled tankers over 200,000 DWT is so small that no statistical inference can be made about the effect of increased astern horsepower on large tankers.

Stern Anchor - Since most CRG casualties occur in restricted and shallow water, the use of an anchor system as a drag where favorable conditions exist has some potential for reducing stopping times and distances for smaller tankers, but only as a last resort. Results are similar for bow and stern anchors. A stern anchor allows more directional control during maneuvers. For the baseline ship, classification society rules require the following anchors for the 40,000 DWT and 84,000 DWT vessels.

	Weight of Anchor in Long Tons	Length of Chain in m (ft)
40,000 DWT	5	290 (950)
84,000 DWT	9	335 (1100)

Table 12 - Accident Rates for Steam Propelled and Motor Propelled Vessels for the Years 1969 through 1977

	Steam Propelled			Motor Propelled		
Size Range	Tanker Accidents	Operating Years	Accident Rate	Tanker Accidents	Operating Years	Accident Rate
100,000 149,999	37	590	.063	60	1350	.044
150,000-199,999	20	425	.047	13	281	.096
200,000-249,999	92	1742	.053	3	104	.029
250,000 & Up	38	1175	.032	1	89	.011
Total	187	3932	.048	77	1824	.042

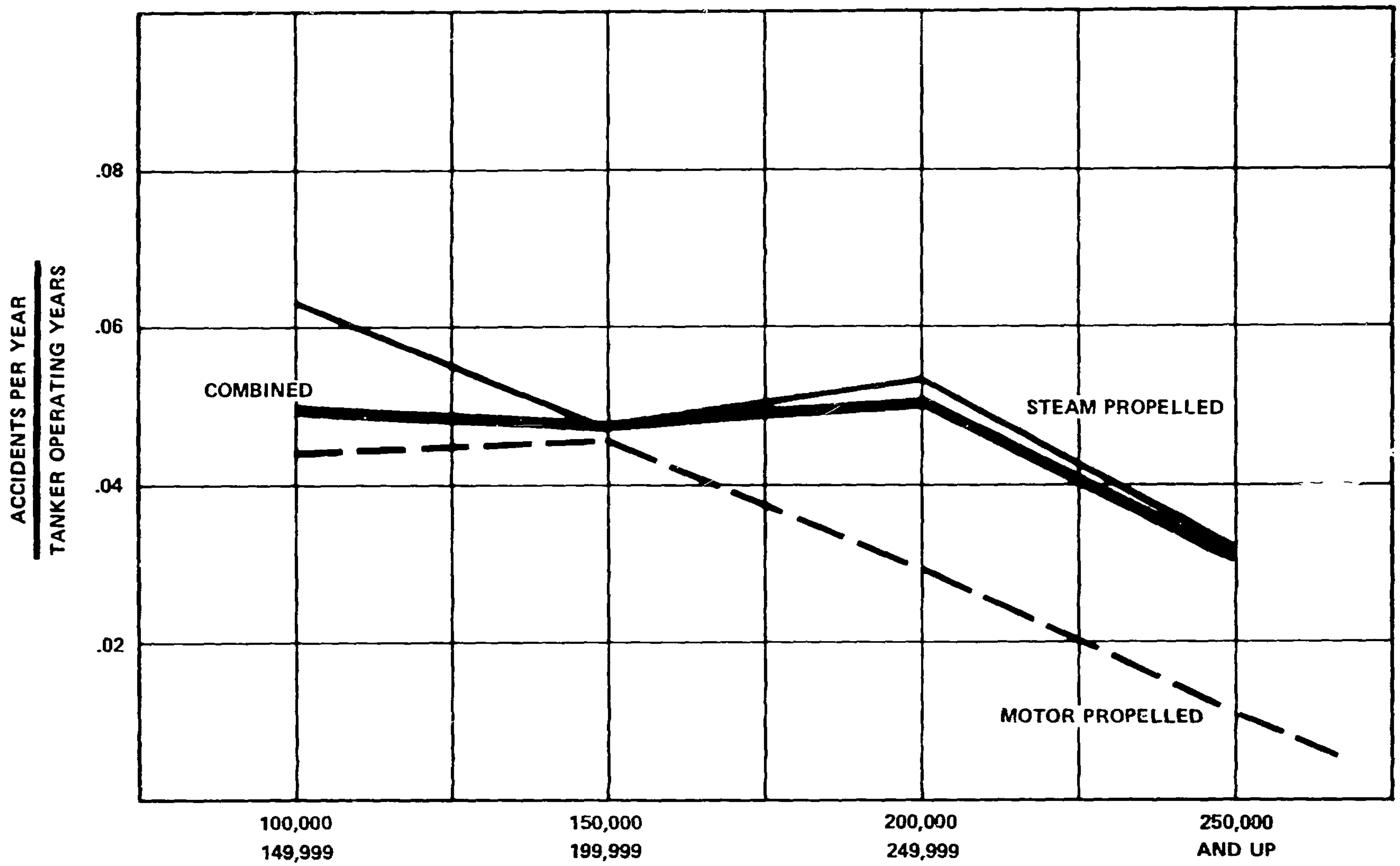


Figure 24 - Accident Rate of Steam and Motor Powered Tank Vessels Larger Than 100,000 DWT for the Years 1969 through 1977

Since the anchor would be used as an emergency stopping device, the anchor windlass and handling gear must be designed for rapid operation and high loads. Deck machinery that meets such requirements is not within the practical limits of size, complexity, and operation for marine use. In addition, tunnels, cable crossings, pipelines, and other submerged objects may be damaged, or they may damage the anchor system if it is deployed around them.

Tunnel Thruster - Tunnel thrusters are useful at low ship speeds when the effectiveness of the conventional rudder is reduced. For the purpose of this study each of the ships was equipped with standard size bow thrusters. They are designed to provide a turning rate of 8 to 9 degrees per minute at low speeds. The number and size of the units for each vessel is as follows:

	No of Thrusters	HP per Thruster
40,000 DWT	1	2000
84,000 DWT	1	3000
280,000 DWT	2	3000

Costs for 1981 delivery dates for new and retro-fitting of thrusters for representative Maritime Administration vessels are:

Tanker	New	Retro-fit
T6	$350,000	$470,000
T8	$650,000	$890,000
T10	$1,760,000	$2,340,000

Active Rudder - The active rudder shown in Figure 17 consists of a submerged electric motor contained in a streamlined casing, set within the normal rudder. The active rudder's small propeller is usually encased in a Kort nozzle duct. The unit improves maneuvering performance at low and zero speeds, both ahead and astern. The tandem arrangement of an active rudder unit directly behind the propeller increases efficiency compared to the propeller alone. The horsepower for the active rudder units are:

	Horsepower for Active Rudder
40,000 DWT	400
84,000 DWT	600
280,000 DWT	900

Controllable Pitch Propellers - Most diesel and gas turbine powered vessels are equipped with controllable pitch propellers because their engines have limited RPM ranges or cannot be run in reverse. The propeller blades can be adjusted to reverse thrust while the engines and propeller continue to rotate in the same direction. This device is similar in effect to increased

astern horsepower for steam vessels. Although full engine power can be applied to the propeller, the efficiency of the blades is lower in the astern mode, so reverse thrust is approximately 80 percent of forward thrust. The accident analysis for diesel and steam tankers applies equally well to tankers having controllable pitch propellers. This device can be used in large tankers and other high power applications. The initial and maintenance costs for the propeller and controls are high. Typical initial costs are:

Tanker	Cost
T6	$700,000
T8	$1,170,000
T10	$2,340,000

Steerable Kort Nozzle - This device provides higher efficiency of the hull and propeller than the conventional arrangement and gives significantly better maneuvering qualities. The steerable Kort nozzle used for the 84,000 DWT tanker simulation was scaled for the 40,000 DWT and 280,000 DWT ships. This device requiries a complicated design procedure, larger steering gear, and higher initial cost. For large tankers, construction and operation of this nozzle are serious problems, and it has not been applied to large tankers.

RESULTS OF MANEUVERING DEVICES FOR THE MARITIME ADMINISTARTION STANDARD SERIES

The maneuvering device study for a large tanker (280,000 DWT) is in response to the Presidential Initiative. It is apparent that few of these devices can make significant improvements to large tankers. However, the devices could improve the maneuverability of small vessels. Since the overall objective of this effort is to reduce oil outflow from CRG accidents, smaller tankers were also examined to provide an appreciation of device effectiveness for a range of tankers. Standard maneuvers are explained and the measure of controllability that it portrays is presented.

Turning Circles - These maneuvers are simulated for an approach speed of 8 knots in shallow water. Each of the Figures 25, 26, 27 shows the basic trajectory of the vessel, along with the values non-dimensionalized by dividing by ship length. The trajectory of the baseline vessel and the vessel with various maneuvering devices in a hardover turn are superimposed. It can be seen from the three figures that the most effective device is the Kort nozzle. Due to the speed of advance a bow thruster has little effect, while the twin screw and rudders results in some increased turning ability as seen by decreases in advance and radius of turn.

Figure 28 provides the relationship of the maximum advance, defined in Figure 4 as a function of tanker deadweight and illustrates the reduction in

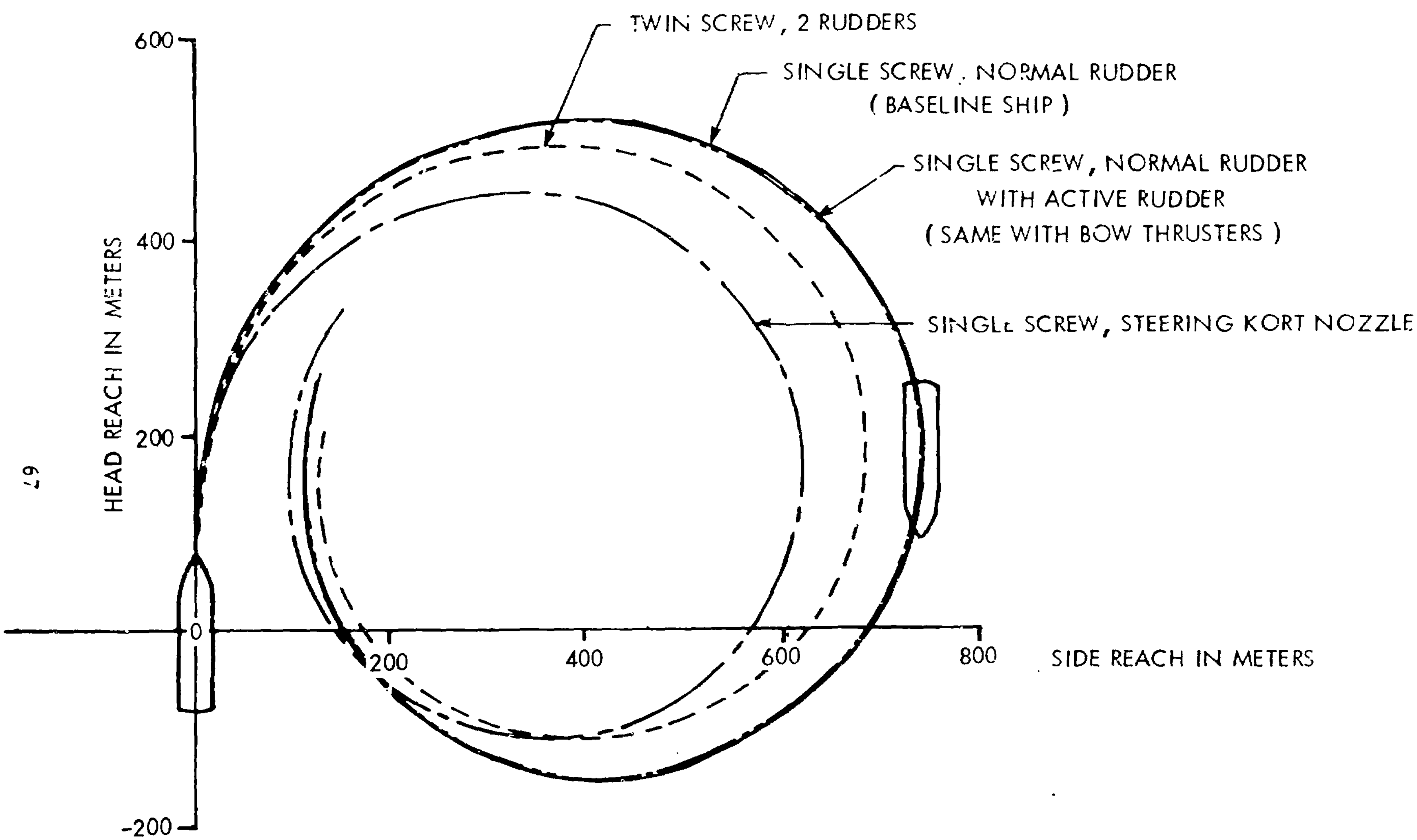


Figure 25 - Comparison of Paths for 40,000 DWT Ship Turning in Shallow Water

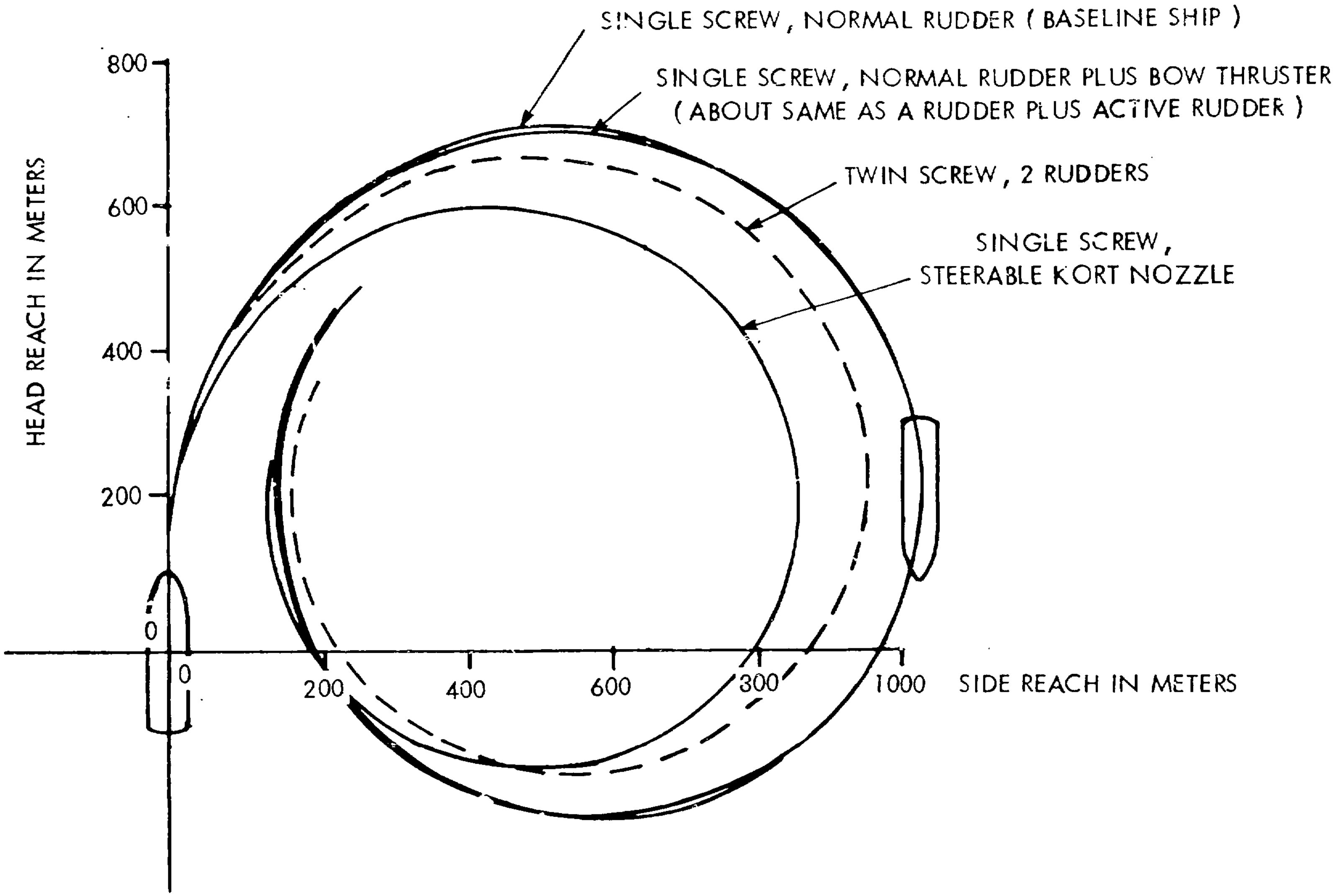


Figure 26 - Comparison of Paths for 84,000 DWT Ship Turning in Shallow Water

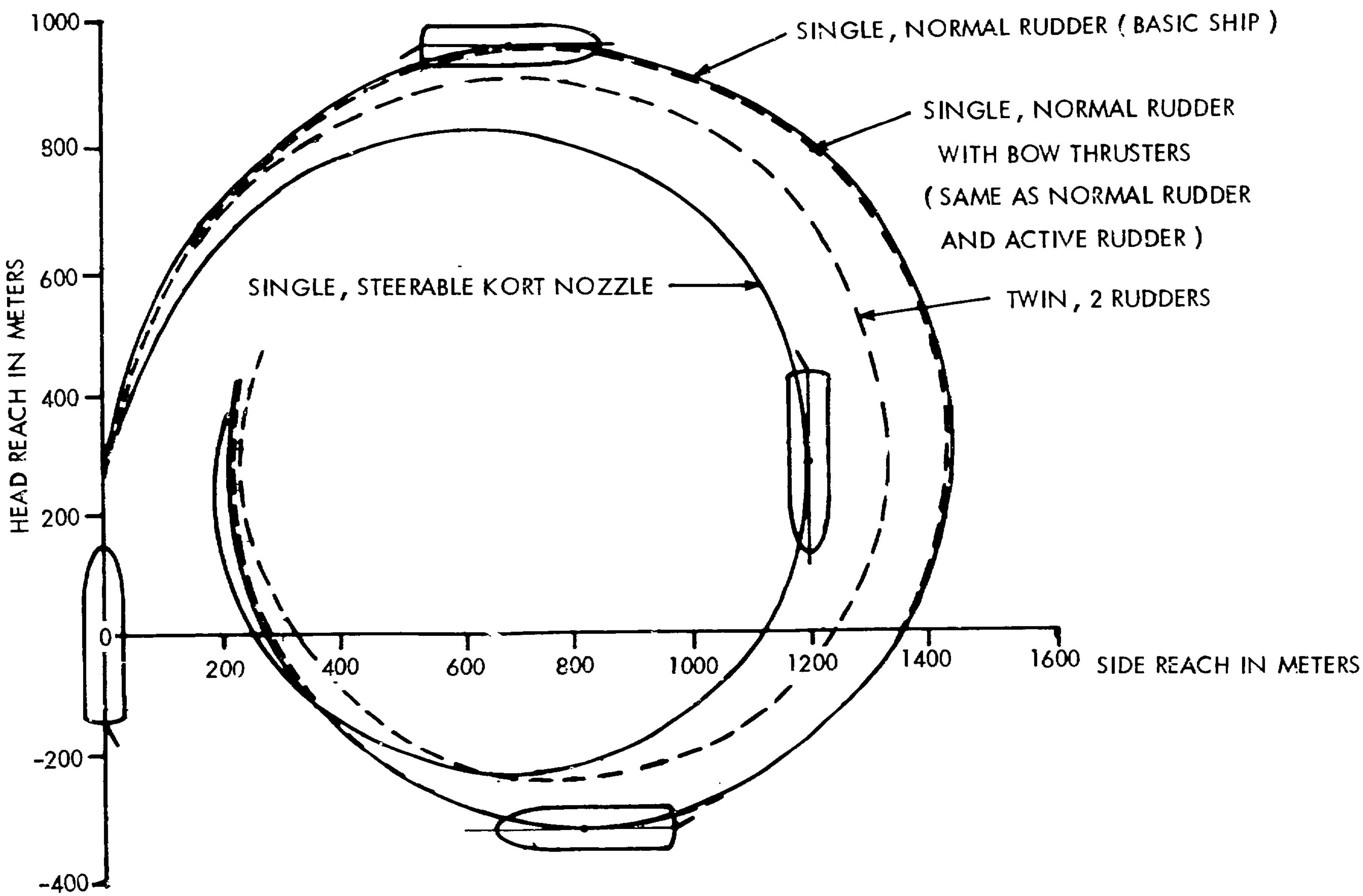


Figure 27 - Comparison of Paths for 280,000 DWT Ship Turning in Shallow Water

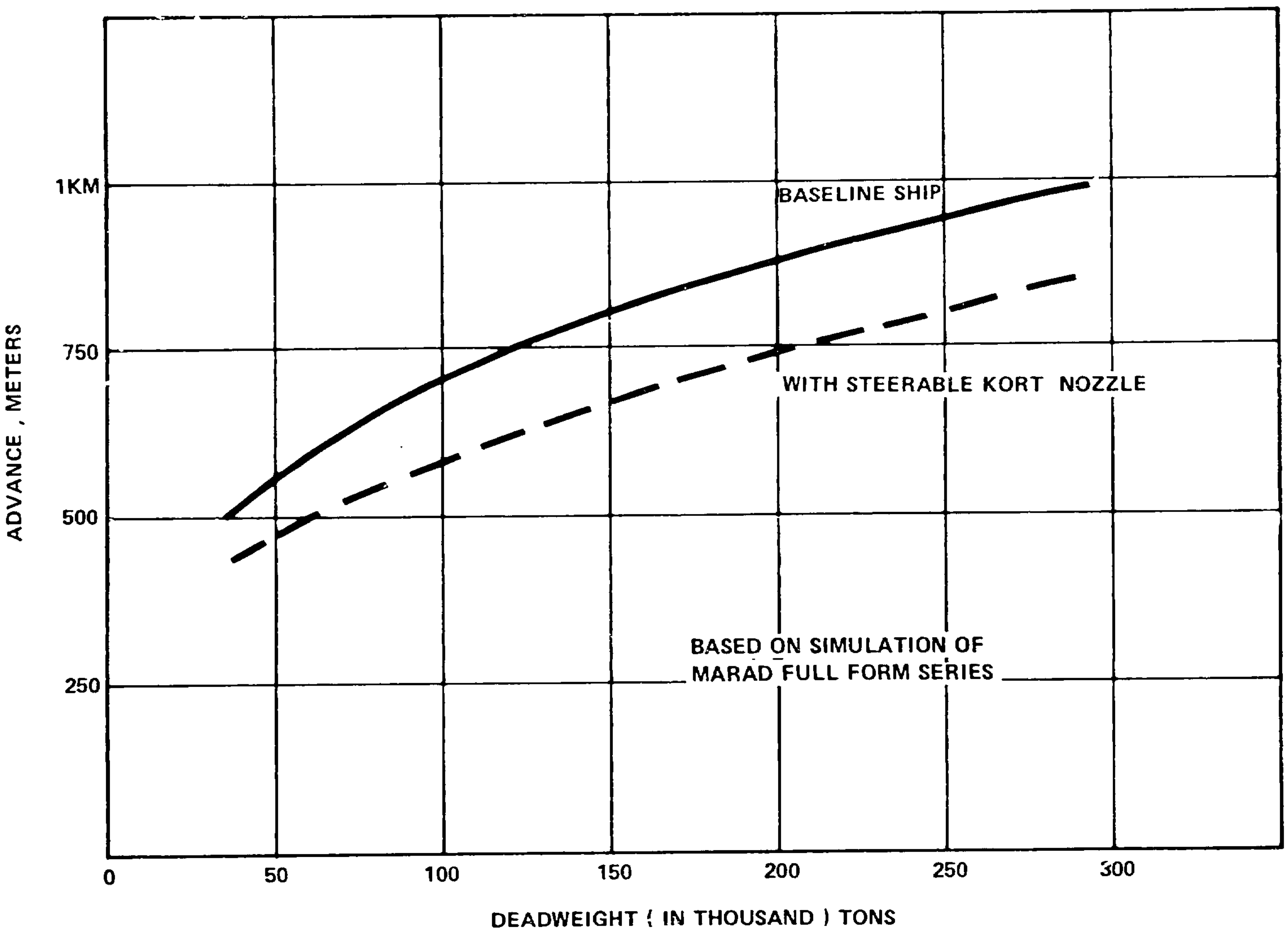


Figure 28 - Maximum Advance from Turning Maneuver from Approach Speed of 8 Knots in Shallow Water

advance that can be achieved with steerable Kort nozzles. These results are tabulated below:

	Reduction in Advance (m)	Length (m)	Reduction/ Length
40,000 DWT	75	160	0.46
84,000 DWT	110	206	0.53
280,000 DWT	130	308	0.42

<u>Accelerating Turn</u> - These results are presented in Figures 29 through 31 for the three vessel sizes and combined in Figure 32 as a function of deadweight. There is no clearly effective device for reducing the advance, considering the magnitude of the reductions compared to vessel length and beam. Although these figures illustrate execution of the maneuver at zero speed the results are similar if executed at slow (maneuvering) speeds. The comparitive results of Figure 32 show that the reduction in advance with the bow thruster is an improvement of only about one-third of a ship length over the entire deadweight range:

	Reduction in Advance (m)	Length (m)	Reduction/ Length
40,000 DWT	55	160	0.34
84,000 DWT	60	206	0.29
280,000 DWT	90	308	0.29

<u>Crash Stop</u> - The results of the crash stop, (Figures 33 through 36) illustrate that twin screws and rudders are more effective than increased astern horsepower as a stopping device. The table below summarizes the significant results of the figures:

	Length (m)	* * * Reduction in Advance (m) * * *			
		Increased Astern HP	by Length	Twin Screw	by Length
40,000 DWT	160	230	1.4	250	1.6
84,000 DWT	206	260	1.3	300	1.5
280,000 DWT	308	300	1.0	400	1.3

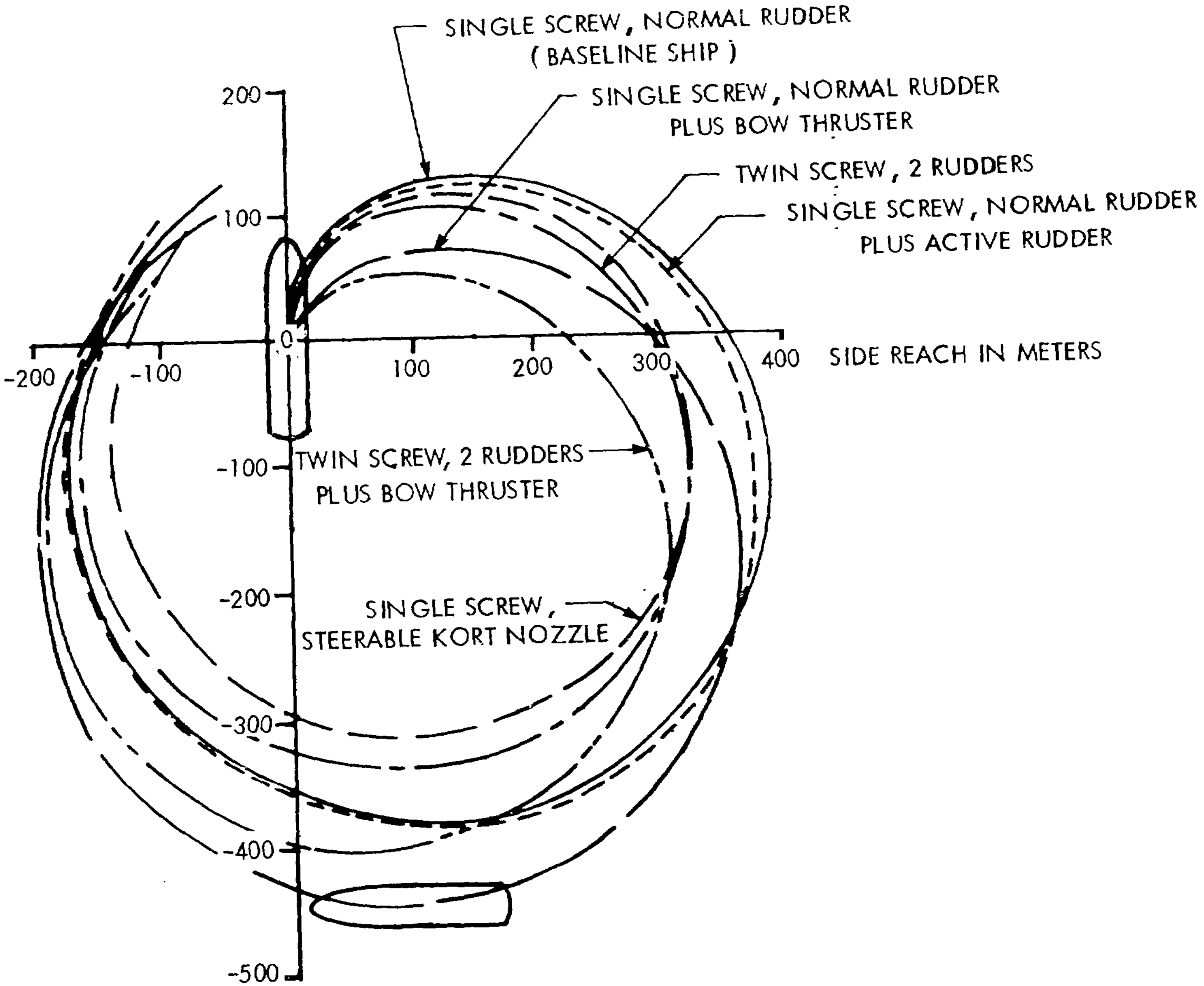


Figure 29 - Comparison of Paths of 40,000 DWT Ship in an Accelerating Turn in Shallow Water

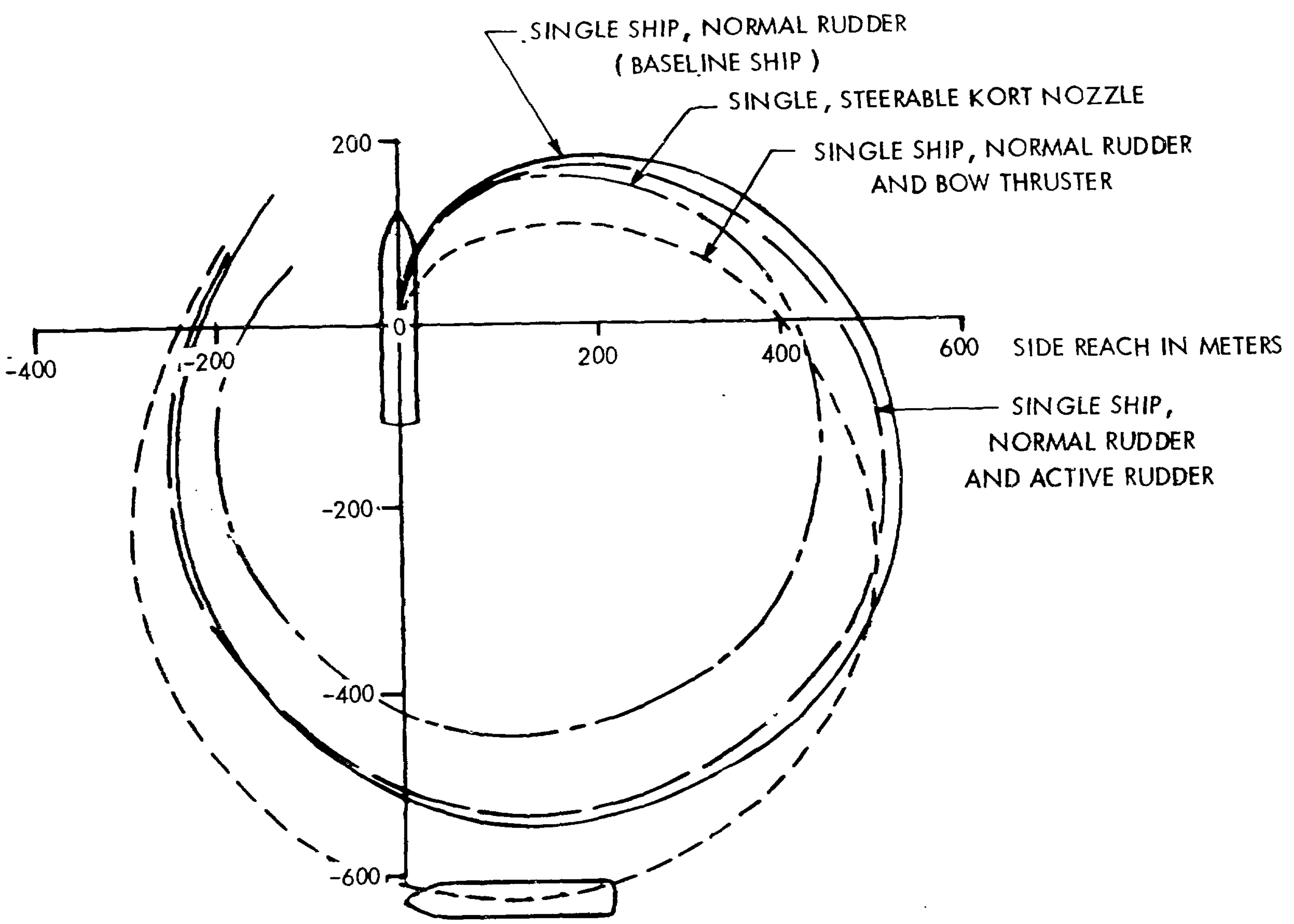


Figure 30 - Comparisons of Paths for 84,000 DWT Ship in an Accelerating Turn in Shallow Water

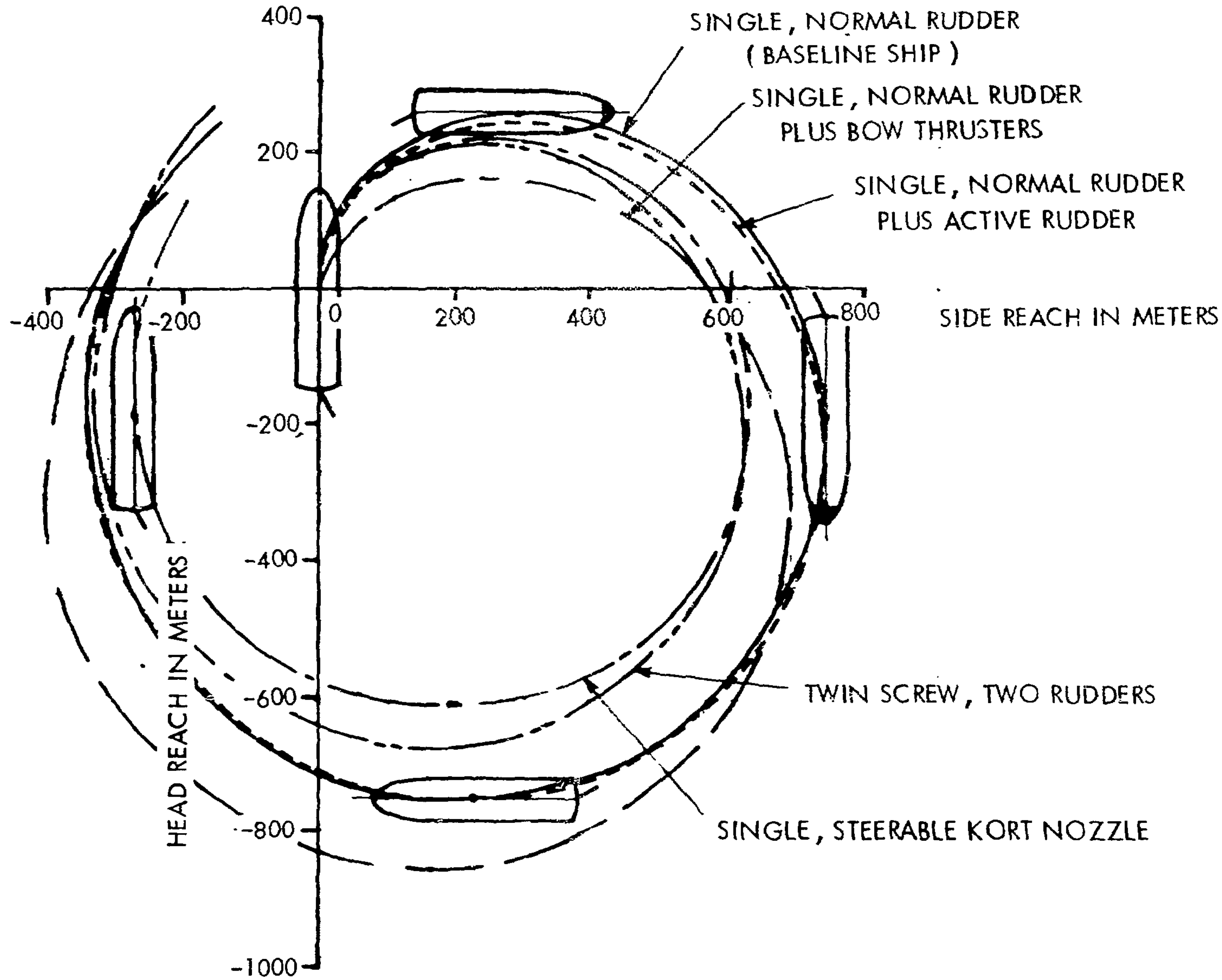


Figure 31 - Comparison of Paths for 280,000 DWT Ship in an Accelerating Turn in Shallow Water

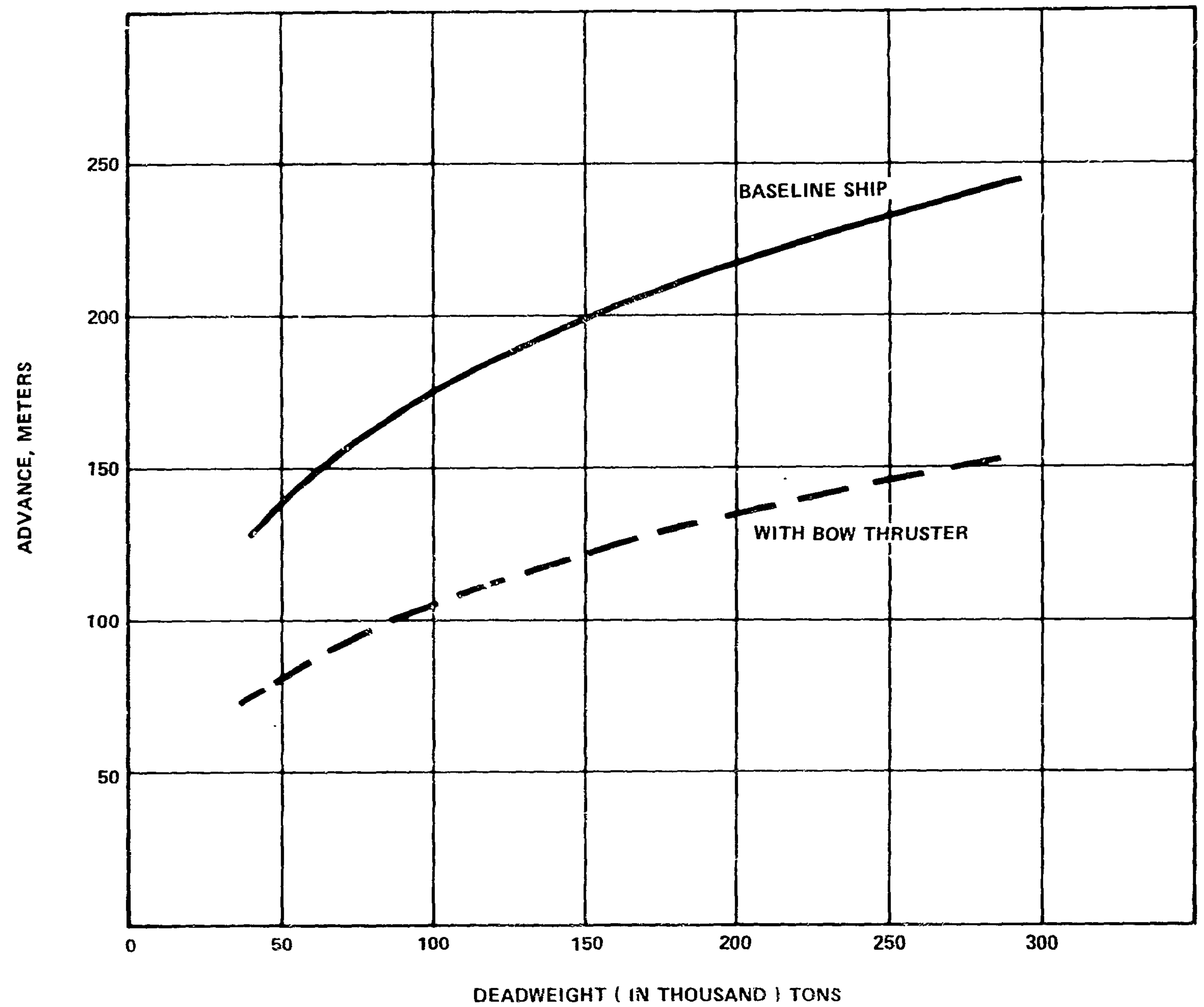


Figure 32 - Maximum Advance from Accelerating Turn for Vessels in Shallow Water

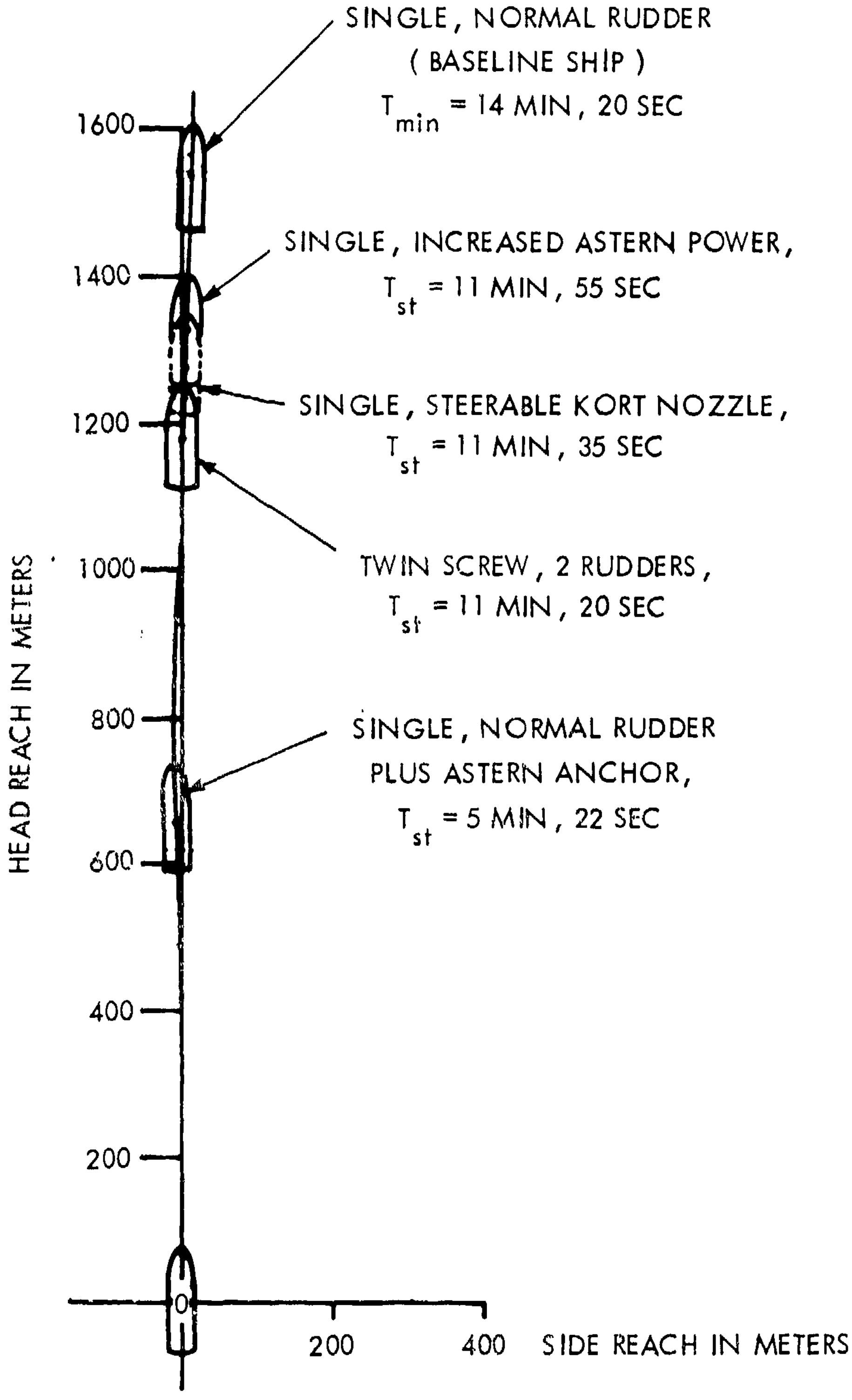


Figure 33 - Comparison of Paths for 40,000 DWT Ship during a Crash Stop in Shallow Water

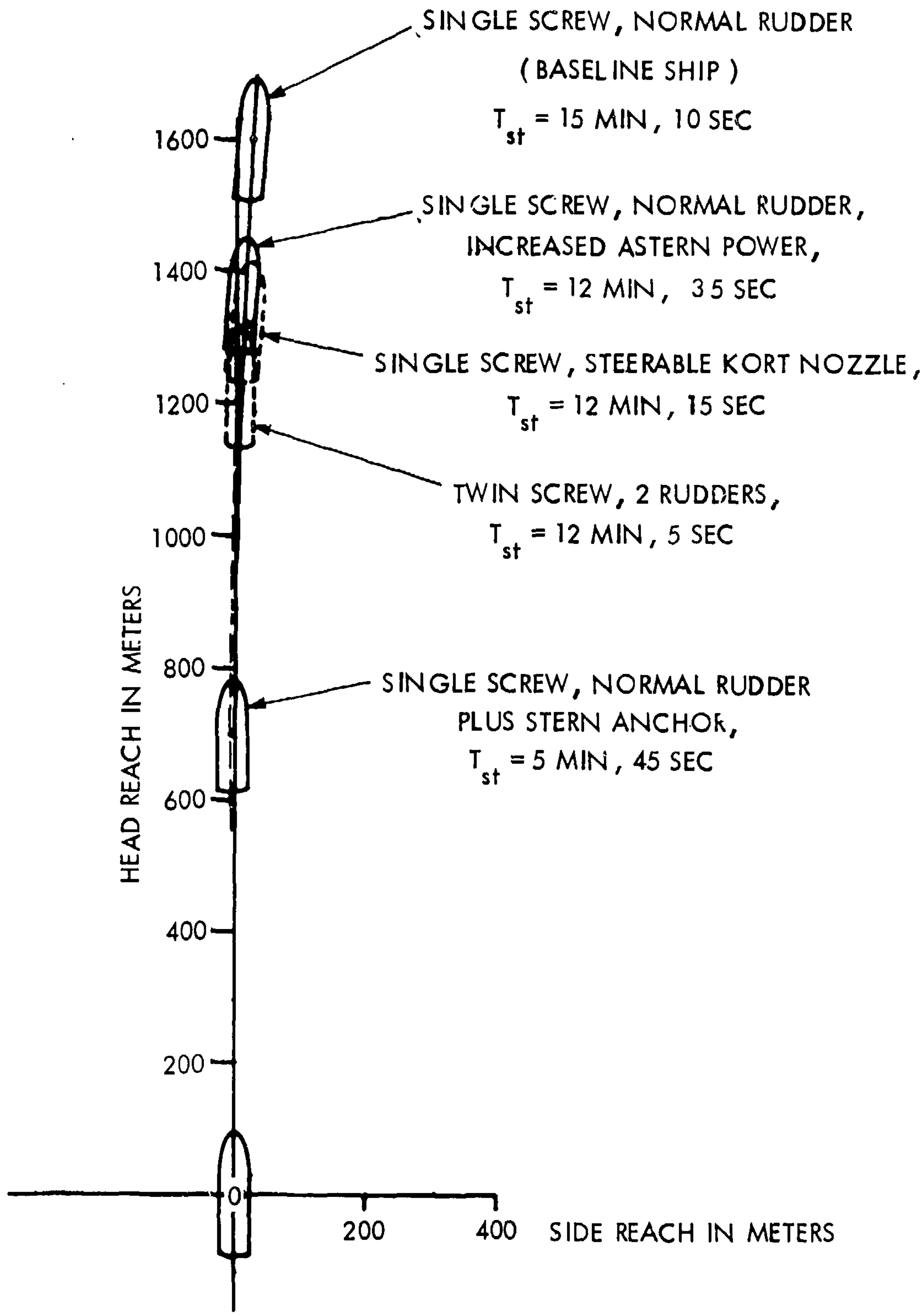


Figure 34 - Comparison of Paths for 84,000 DWT Ship during a Crash Stop in Shallow Water

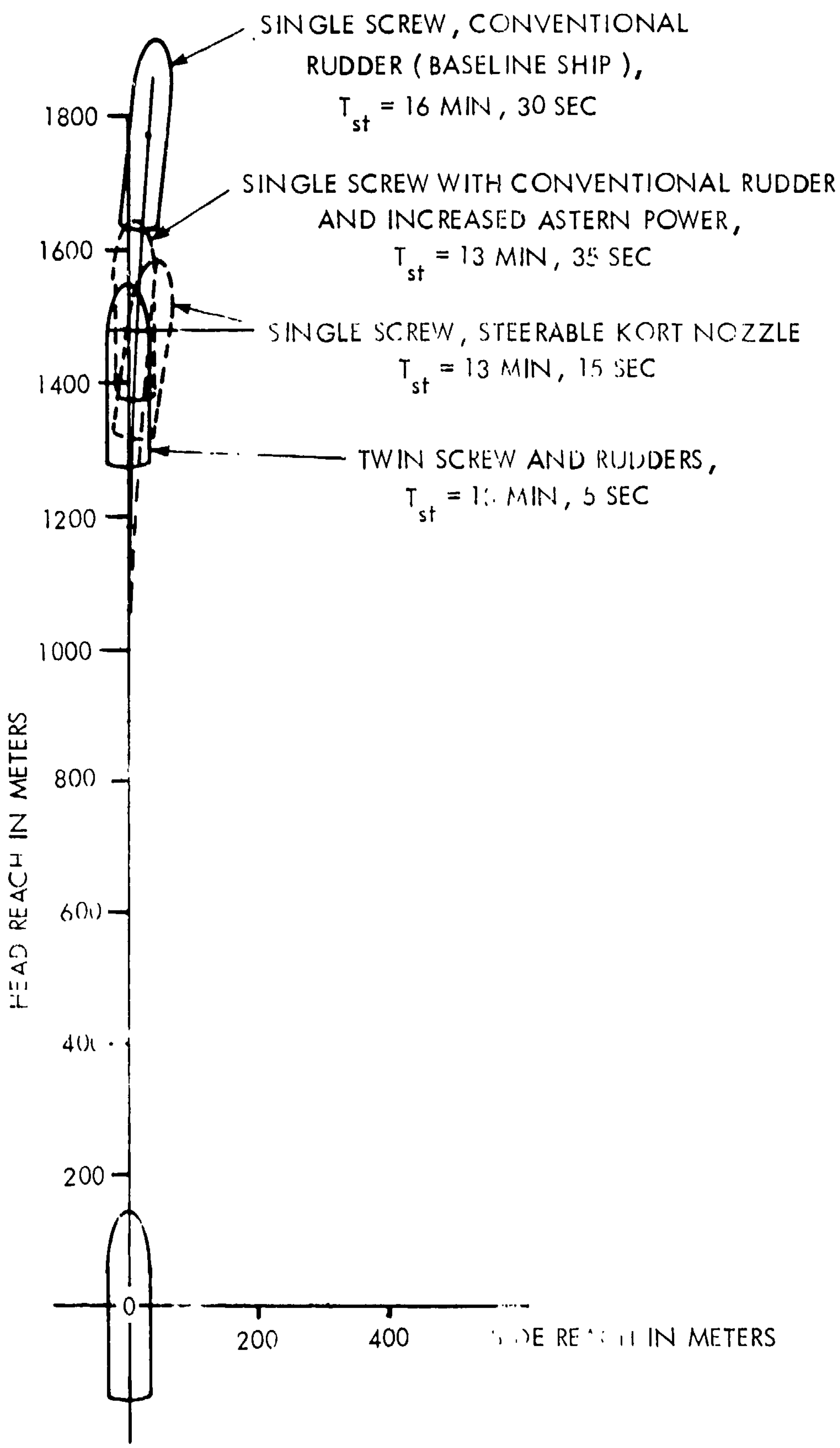


Figure 35 - Comparison of Paths for 280,000 DWT Ship during a Crash Stop in Shallow Water

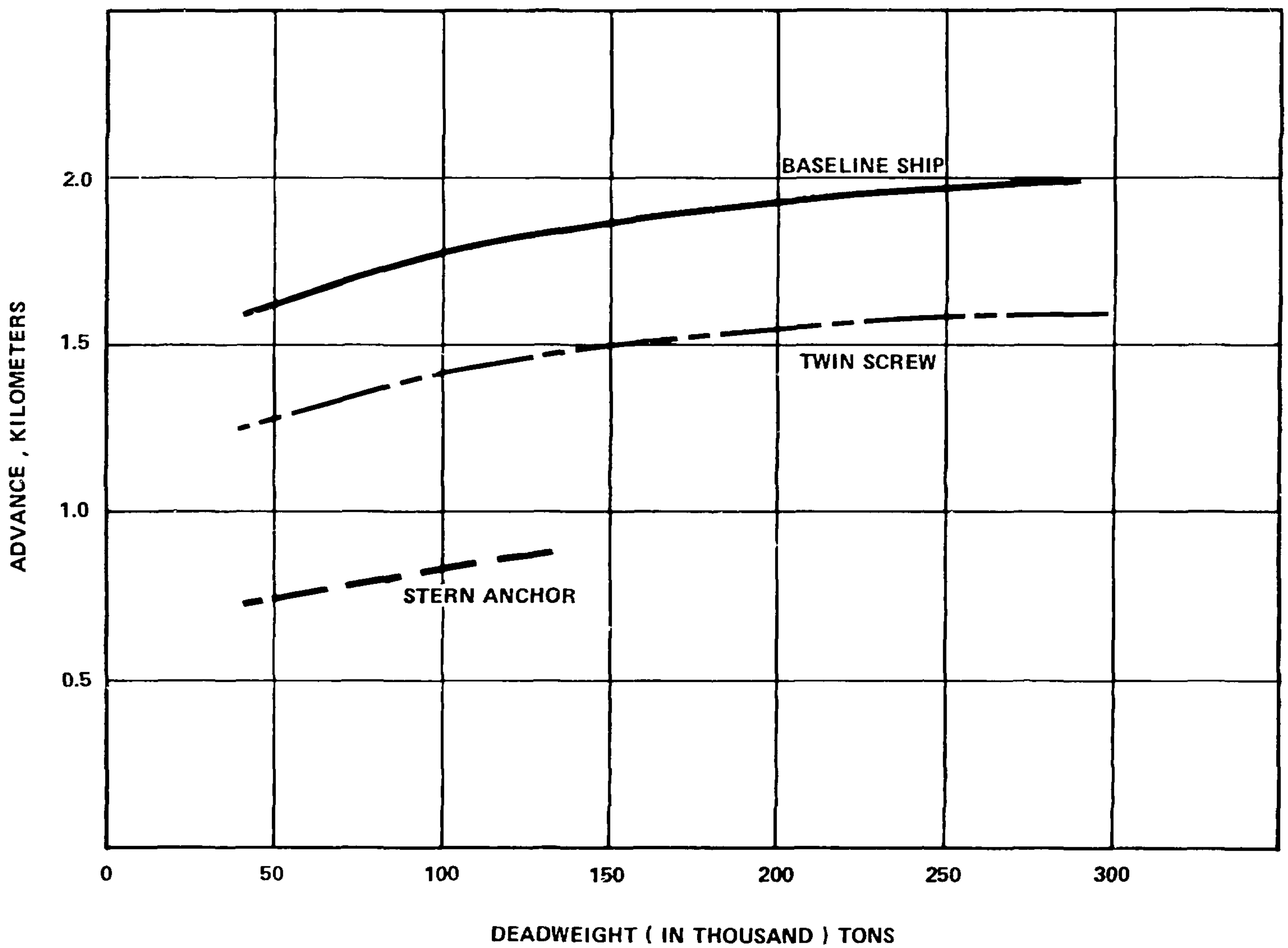


Figure 36 - Maximum Advance from Crash Astern from Speed of 8 Knots in Shallow Water

Section VI
OPERATIONAL TECHNIQUES AND METHODS

GENERAL DISCUSSION

Operational techniques and methods are generally independent of vessel equipment, design, or construction. They can be applied to any vessel with varying degrees of success. Some of the methods, such as transiting a channel at reduced speed increase operating costs. Some of the methods require additional training of the officers, and this is an area in which a real time simulator can be used effectively.

Table 13 lists maneuvering techniques, along with a subjective evaluation of utility. The measure of how well a technique works is the same as for the devices. The second index is based on the difficulty of the maneuver rather than the size or cost. The third index in the table pertains to whether or not the technique has been used on large tankers.

Slower Approach Speed - The common sense approach to reducing stopping time and distance is to be going slow when a situation arises that demands that the vessel be stopped. When reducing the speed of the vessel, however, a period of reduced controllability occurs due to the loss of flow over the rudder. Figure 37 displays the effect of vessel size on stopping distance. It shows that the distance required to stop a 200,000 DWT vessel from 6 knots is 1220 m (4000 ft.) and from 15.5 knots it is 4250 m (14,000 feet). Reducing approach speed by 61 percent reduces stopping distance by 71 percent.

This has been recognized. Figure 38 has been extracted from a training publication for ship officers. The lower curve shows the stopping distance as a function of approach speed for an 18,000 DWT tanker, and the upper curve is for a 210,000 DWT vessel. Representative values from this figure are:

	Stopping Distance, meters	
	4 knots	8 knots
18,000 DWT	325	740
210,000 DWT	550	1670

This shows that a 50 per cent reduction in approach speed reduces the stopping distance by 67 per cent for the larger tanker and 56 per cent for the smaller tanker. Two important conclusions regarding the relationship of vessel size to stopping distance are seen from these figures:

* Slower approach speeds yield greater reduction in stopping distance for larger vessels.

* Slower approach speed reduces stopping distances for all size vessels.

Table 13

Performance Indices for Operational Techniques and Methods to Improve Maneuverability and Controllability

	Maneuver-ability	Diffi-culty	on large tankers
Slower Approach Speed	A	A	A
Hard-over Rudder	A	B	A
Propeller Kick	B	B	A
Rudder Cycling	C	C	B
Traditional Tug	B	B	A
Tug Used as Rudder or Brake	A	B	B
Alongside Tug	B	B	A

Index	Improvement in Maneuverability	Difficulty to Perform	Technique Applied on Large Tankers
A	Significant	Low	Yes, Operational
B	Moderate	Moderate	Yes, Experimental
C	Slight	Significant	No

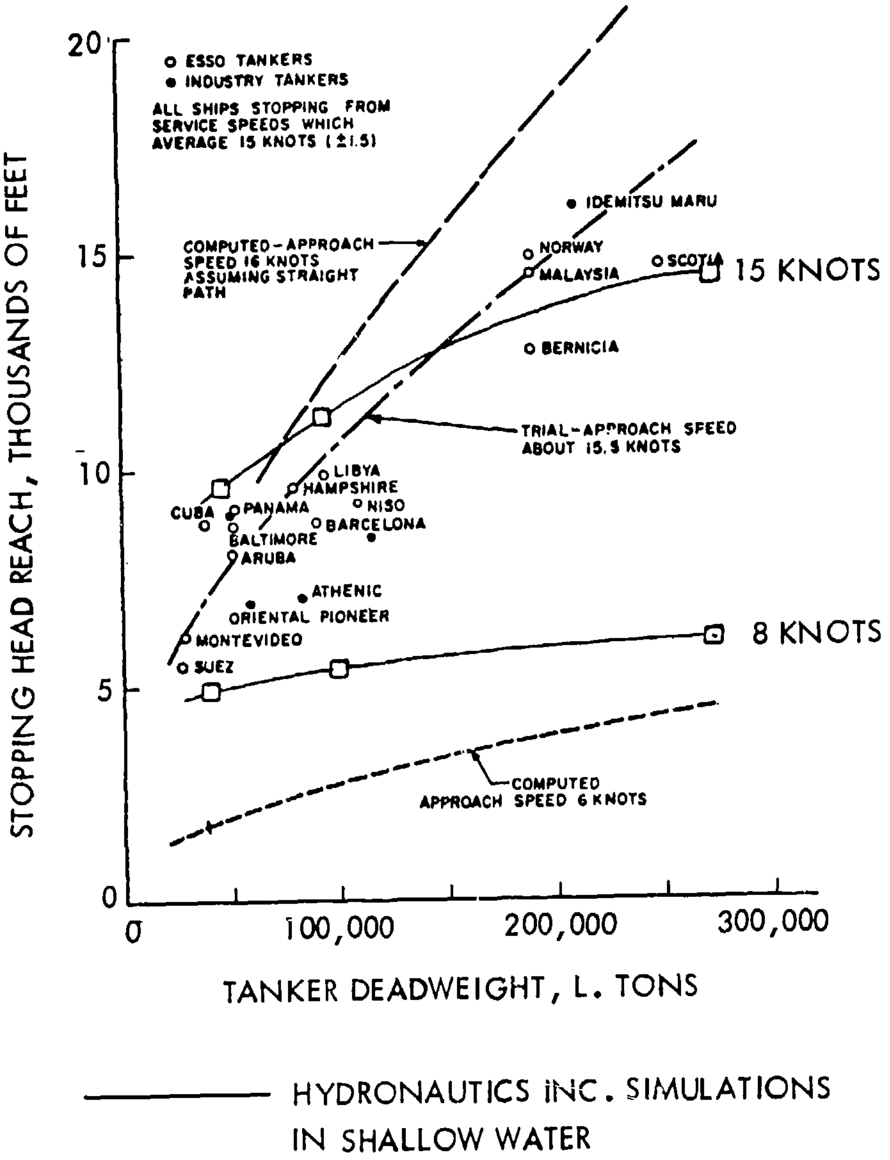


Figure 37 - General Effect of Ship Size on Stopping Head Reach

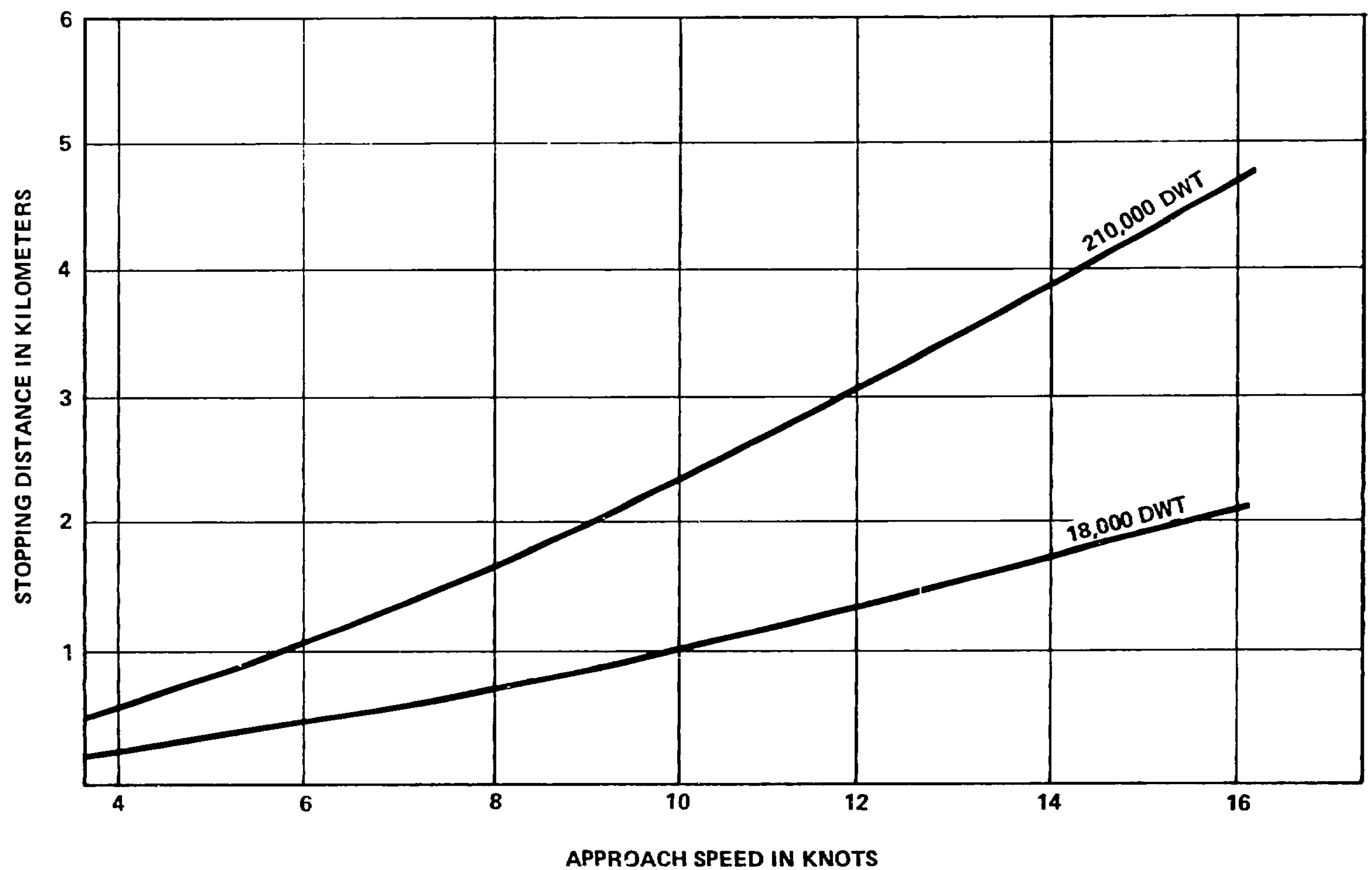


Figure 38 — Stopping Distances for Two Tank Vessels Excerpted from Maneuvering Text Book Prepared for Ship's Masters

This is illustrated by the slope of the two curves in Figure 38. The curve for the 210,000 DWT vessel is much steeper than that for the 18,000 DWT tanker. The two curves (8 knots and 6 knots) at the lower portion of Figure 37 are nearly flat, as compared to the steeper dashed curve representing the computed stopping distance for an approach speed of 16 knots.

There are some problems with slower approach speeds. Wind and current conditions require vessels to increase speed to maintain desired track. Steam turbine power plants can operate at any speed, but diesel engines cannot operate below about 70 percent of rated RPM. The net effect is that at slow to moderate speeds, a direct drive single screw motor propelled vessel must continually stop and start to maintain a low speed. The normal practice is to proceed at higher speed where continous operation can be maintained and to use braking tugs in tight situations.

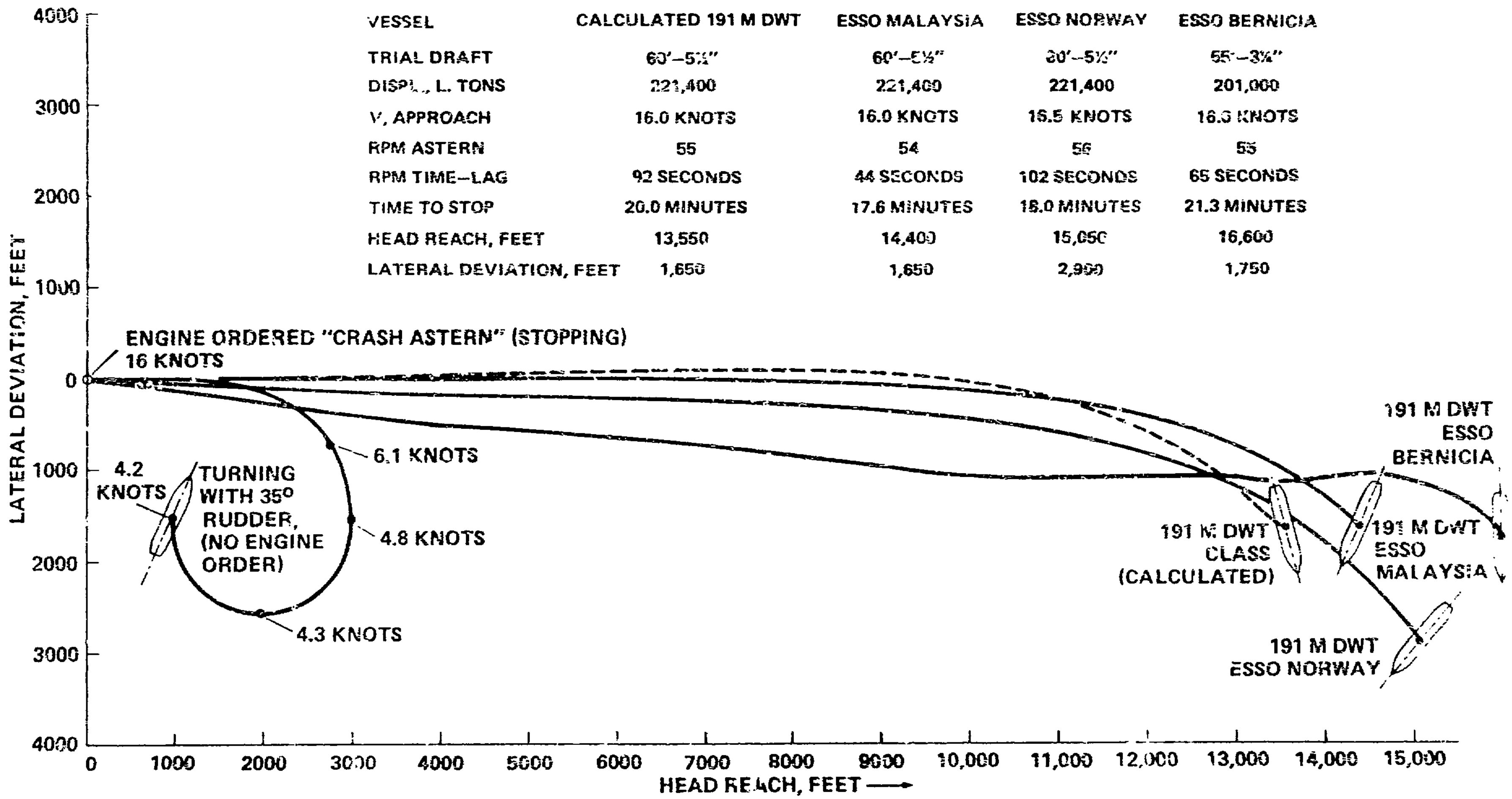
Hard-Over Rudder - This technique utilizes the large drift angle of a tanker to reduce the forward speed by executing a maximum rudder angle turn. It reduces the advance significantly but requires two ship lengths of sea room to steer the vessel off its original track. Both results are potential collision avoidance procedures. This is not discussed further but is illustrated in Figure 39. A five fold reduction in head reach or advance can be achieved by execution of a hard-over turn.

Propeller-Kick - This technique is especially effective for large tank vessels because it does not increase vessel speed. The technique is used at dead slow or slow speeds to move the vessel quickly. It is executed by first applying hard rudder, then ordering about half speed revolutions. The increased flow over the rudder generates an extremely large force which results in the rapid turning of the vessel. This technique is considered further.

Rudder Cycling - This technique, when first proposed appeared very effective, but subsequent trials and studies have failed to substantiate this. It is intended to reduce the stopping distance and time from full speed. There are various types of cycling but the most common requires complicated throttle and helm commands and close attention to the vessel's course, heading, and turning rate. For a 191,000 DWT tank ship approaching at 16 knots the rudder cycling maneuver takes about 10 minutes. Recent trials on the ESSO OSAKA have found the technique provides very little improvement in stopping time or distance. No further consideration of this technique is given.

Tugs - Recently there has been interest in expanding the traditional use of tugs. The proposal has been to see how tugs could assist the propulsion/rudder system of large tankers in normal and emergency maneuvering situations at moderate speeds. The Rudder Tug, Braking Tug, and Alongside Tug are arrangements for tug assistance. The use of tugs is summarized below.

Traditional Tug - This technique is commonly used in ship berthing at vessel speeds below two or three knots. It does not require special thrusting or powering arrangements for the tug. No further discussions of this will be provided.



VESSEL	CALCULATED 191 M DWT	ESSO MALAYSIA	ESSO NORWAY	ESSO BERNICIA
TRIAL DRAFT	60'–5½"	60'–5½"	60'–5½"	55'–3¾"
DISPL., L. TONS	221,400	221,400	221,400	201,000
V, APPROACH	16.0 KNOTS	16.0 KNOTS	16.5 KNOTS	16.3 KNOTS
RPM ASTERN	55	54	56	55
RPM TIME–LAG	92 SECONDS	44 SECONDS	102 SECONDS	65 SECONDS
TIME TO STOP	20.0 MINUTES	17.6 MINUTES	18.0 MINUTES	21.3 MINUTES
HEAD REACH, FEET	13,550	14,400	15,050	16,600
LATERAL DEVIATION, FEET	1,650	1,650	2,900	1,750

Figure 39 – Comparison of Calculated "Crash Astern" Maneuvers with Full Scale Trial Results (ESSO 191,000 DWT Tanker, Load Condition)

Escort - This function involves tugs operating with a vessel, but not attached. Should an emergency arise, the tugs would be near the vessel to lend assistance.

Assistance - This function involves tugs attached to or in contact with a vessel for the purpose of braking, stopping, or keeping a vessel within a desired swept path. Tug assistance can be accomplished through one or more of the following three arrangements:

Alongside Tug - The alongside arrangement is an effective way to provide immediate auxiliary power and maneuverability to a ship transiting a congested or restricted waterway. This arrangement can augment the vessel's steering and braking for vessel speeds below three knots, and it can augment braking up to speeds of 6 to 8 knots. Tests have shown that in winds up to 40 knots and at speeds up to about 8 knots, control of the ship may be maintained in some cases by tugs, even if the ship's rudder is stuck in a hard-over position. At least one tug must be provided on each side of the tanker, and more tugs may be required depending on individual conditions. This arrangement is also an effective way to reduce stopping distance.

Braking Tug - This arrangement is generally considered to be with the use of a tension line (hawser) attached to the stern of the ship, with the other end through a bridle or special winching arrangement on the tug, which faces in the opposite direction. Ahead thrust by the tug applies a retarding force on the tanker. With additional equipment on the tug it may provide turning assistance by pulling at an angle relative to the ship. Additional studies have been conducted in Japan, and the practice is common in some ports.

Rudder Tug - This technique incorporates various concepts to form a large rudder and stern attachment for turning thrust. With the tug secured to the aftermost part of the tanker, application of thrust and rudder by the tug imparts a turning moment to the tanker. Special winches on the tug permit expanded flexibility in control by the tug. Rudder tugs have been tested and are in common use in the Panama Canal. The technique was used in San Francisco harbor a number of years ago. This concept was also tested in two Coast Guard sponsored programs to assess ship maneuverability after equipment failure. This is discussed in more detail later in this report. It has been proposed that a tug equipped with flanking rudders could also provide controlled braking.

EVALUATION OF TUG ARRANGEMENTS

The studies undertaken by the Coast Guard, relate to the Coast Guard's responsibility to investigate the maneuvering capabilities of tank vessels within enclosed and confined waterways such as Puget Sound, Port Valdez, or the Chesapeake Bay, and to determine the need for regulations governing their passage. These regulations might involve:

- Recommended safe maximum or minimum ship speeds under specified

environmental conditions (wind, current).

* Critical harbor areas where special precautions might be required (tug escort) or constraints based on environmental conditions or ship displacement and tonnage.

* The need for tugs.

* Procedures to be adopted in case of equipment failure.

There are two major arrangements of the tugs/vessel that are discussed. In each case the tug arrangement schemes were evaluated, although by different means, within the framework presented in Section III. Since the two test and evaluation programs that are reported here address one or more of the tug arrangement schemes, it is much clearer to discuss each of the arrangements within the study.

AN INVESTIGATION INTO SAFETY OF PASSAGE OF LARGE TANKERS IN THE PUGET SOUND AREA

The study investigated safety of passage under maximum credible adverse environmental conditions (40 knot winds, up to 6 knot currents) as follows:

* Track keeping runs in critical portions of four passages in the Puget Sound area, without the assistance of tugs. This provided the baseline vessel performance for subsequent comparison with tug arrangement schemes.

* Runs with engine and rudder failures with no tugs, and with two or four tugs assisting the vessel by providing astern thrust parallel to the ship's centerline. This examined Alongside Tug arrangements.

These techniques were evaluated using a mathematical simulation model which incorporated the human factor. The simulations were conducted at the CAORF facility of the Maritime Administration located at Kings Point, New York. These runs were performed on a computer with maneuvers dictated by a programmed autopilot. These runs were followed by a manned simulation of several of the runs to examine the results of the computer simulation. Five different tankers ranging from 40,000 DWT to 400,000 DWT were used. The conclusions of the initial assessment of unassisted track keeping apply to the most severe tidal current conditions and a wind of 40 knots:

* Vessel size is not a primary variable affecting track keeping capability: the 80,000 DWT and 400,000 DWT vessels held track about equally well. The ratio of rudder area to immersed profile area of the hull appeared to be an important physical factor.

* Very high crab angles (vessel not aimed in the direction of

travel) are experienced for high tidal current conditions at low vessel speeds. Although the autopilot could cope with these conditions, this situation may be considered unacceptable by a human pilot. However, it is expected that a human pilot would periodically increase engine RPM without significantly increasing ship speed to achieve better control and to avoid large crab angles.

The conclusions for the unassisted vessel which experienced engine failure but retained rudder control (with current and 40 knot winds):

* When engine failure occurred at 4 knots, and sometimes at 6 knots, the wind consistently overpowered the rudder and could turn the vessel in a direction opposite to that desired.

* Following currents created the greatest difficulty for vessels. The current carried the vessel along while it was attempting, often unsuccessfully, to turn. Changes in course were impractical; very large advances occured, and speed over the ground remained too high to attempt anchoring.

* With a head-on current, the vessels also could not follow the desired course. By turning into the current these vessels were generally able to reduce their speed over the ground to speeds at which anchoring might be feasible. Varying the delay time before heading into the current demonstrated that increased delay in the time at which the vessel turned up into the current resulted in greater transfer (side reach) and also reduced the amount of time available for anchoring. The larger the vessel, the longer the time delay it could tolerate before a turn into the current became of little or no advantage.

* The inability of all the vessels to consistently establish speeds over the ground at which anchoring may be attempted, and the difficulty of maintaining control in a turn, suggest that tug support is needed to guarantee safety in the event of engine failure.

The simulation runs with Braking Tugs assistance upon engine and rudder failure concluded that:

* The use of tugboats to retard the forward motion of the vessel results in an appreciable reduction in the distance traversed and the transfer in particular.

* High magnitudes of transfer occur at ship speeds through the water of 8 knots or more. Tugboat utilization strategies other than pure retardation, which was the only strategy simulated, are required if lower transfers are to be achieved at these speeds. The impact of the use of modern tugs, such as tractor

tugs which can exert appreciable lateral forces at high speeds may be advantageous.

* At speeds less than 8 knots, reasonable magnitudes of transfer can be achieved with retarding tugs. However, these lower speeds may conflict with the requirements for satisfactory track keeping when extremes of current and wind exist. Vessels should be equipped with instrumentation to determine the speed through the water.

EXPLORATORY TANKER/TUG MANEUVERING TESTS

In July 1978, a series of exploratory tests were conducted in the waters of Port Valdez to explore the effectiveness of a tug in controlling the movement of a loaded tanker subject to the simultaneous loss of propulsive power and steering. The techniques that are to be evaluated here are the tug performing as a rudder and the tug augmenting the vessel's braking effort, and they were evaluated in full scale trials. The two vessels participating were a 120,000 DWT tanker and a 5,750 horsepower tug. Nine tests were run to evaluate the use of the tug. There were three major objectives of these full scale tests:

* To ascertain the ability of the tug, pushing and also acting as a partial rudder at the stern, to counter the turning moment of the tanker when it suffered a simultaneous loss of propulsive power and of steering with the rudder in a hard-over position.

* To ascertain the ability of the tug, pushing and also acting as a partial rudder at the stern, to turn the tanker in a tight turn when it suffered a simultanious loss of propulsive power and of steering with the rudder in a hard-over position.

* To ascertain the ability of the tug (initially travelling unattached as escort) to counter the tanker's turn by pushing in the forward half length after simultaneous loss of propulsive power and steering with the rudder in a hard-over position.

For the runs where the tug was secured, the tug was snugged up until its bow fenders were in contact with the tanker's hull. Figure 40 illustrates the results of this arrangement:

* The tug when secured to the stern of the tanker at its centerline, upon simulation of failure of tanker propulsion and rudder at hard left, was able to limit the transfer to port from the following initial speeds:

Speed	Transfer, m (ft)
4	55 (180)
6	440 (1440)

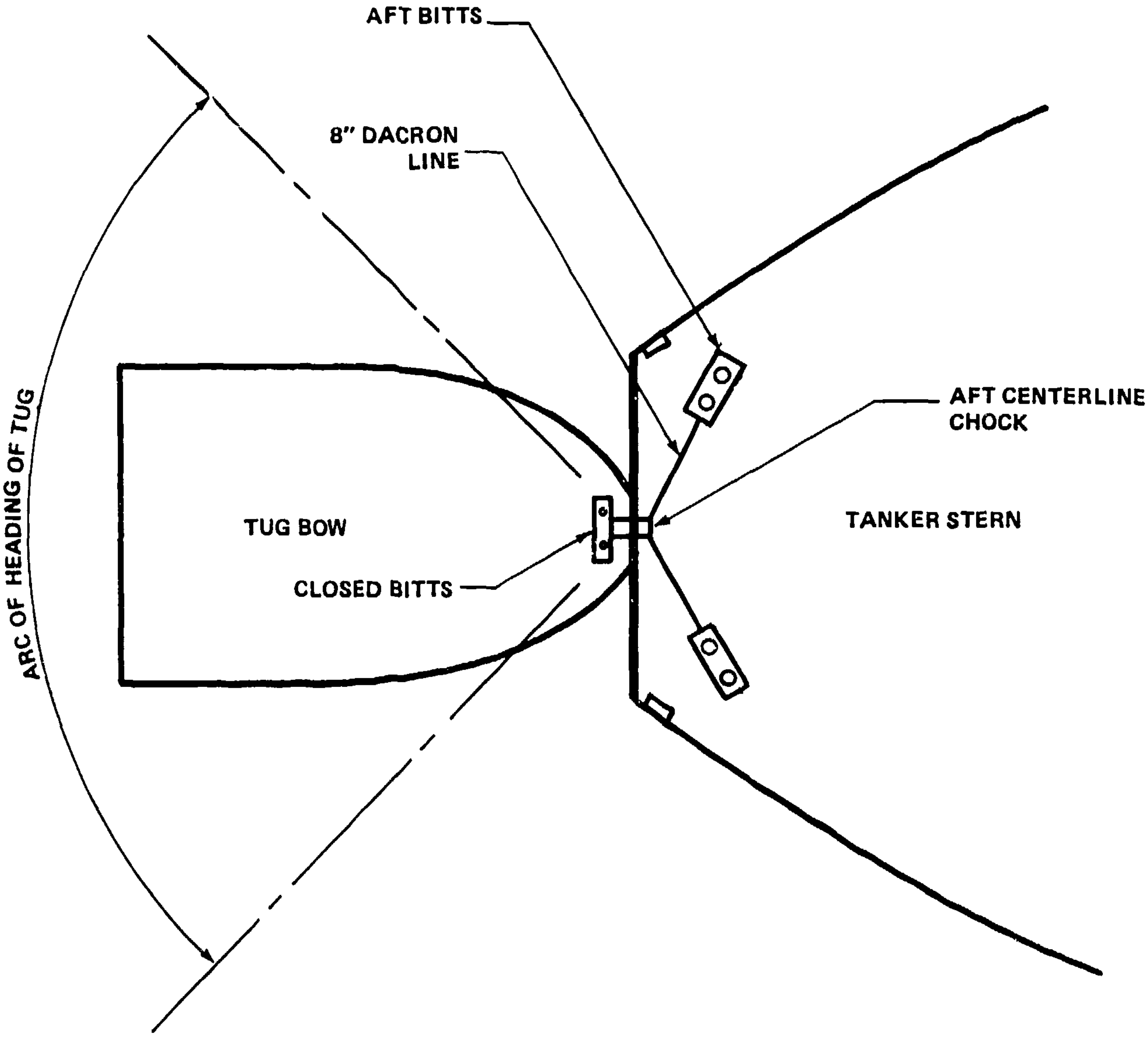


Figure 40 -- Diagram of Tanker and Tug Connection Arrangements for Port Valdez Full Scale Evaluation

* At 8 knots the tug was not able to limit the transfer to port nor restore it to its original heading. The observed transfer to port was about 1370 m (4500 ft).

* With the tug secured to the stern and working to turn the tanker as quickly as possible in a tight turn to an opposite course, the approximate transfers to port were as follows:

Speed	Transfer, m (ft)	
4	550	(1800)
6	730	(2400)
8	820	(2700)

* With the tug in escort off the port quarter, it was able to limit the transfer to port to about 45 m (150 ft) from an initial speed of 3 knots. From an initial speed of 5 knots, this same maneuver resulted in a transfer to port of about 990 m (3240 ft).

SUMMARY OF OPERATIONAL TECHNIQUES

There are numerous techniques which can be executed by the operating personnel of tankers that can improve maneuvering and stopping ability. For example, the hard-over turn can significantly reduce the maximum advance, as contrasted to that of the crash stop maneuver. A slower approach speed is an effective technique for reducing the head reach, whether the vessel is a 40,000 DWT or a 512,000 DWT tanker. Experimental techniques such as the use of tugs for rudder and braking augmentation have been shown to be capable of steering a vessel that has become disabled, or is being affected by extreme environmental conditions.

None of these techniques require increased ship construction costs, but they demand training time and expenses which must be considered. One such means of training for these techniques is a real time, visually aided simulator, like CAORF. Another means of training of masters and mates is explanatory brochures and booklets. Armed with this knowledge, the open ocean on a clear day could become his training ground.

Section VII
SUMMARY OF FINDINGS

* VESSEL DESIGN

This study puts the maneuvering and stopping ability of existing tank vessels into proper perspective. Results from mathematical simulation and full scale trials of tank vessels show that they are not unmaneuverable, but that they can be handled in a reliable and predictable manner. This is not to say that they all maneuver in the same way. The maneuvering characteristics of a tanker are determined by its physical dimensions, the shape of the hull, its power, and the size, type, and location of the rudder. With such design variables, the maneuvering characteristics of ships of conventional design vary widely. In some designs where the owner is concerned about maneuvering and is willing to pay for design studies, maneuvering capabilities have been enhanced. Such is the case with a recently built class of 400,000 DWT tankers. The design called for a low length to beam ratio and the owners were concerned that the ship be capable of adequate maneuvering. Design studies, simulations and model tests were done to address this concern and as a result the ships have very good maneuvering characteristics. On the other hand, there are ships operating with marginal maneuvering characteristics. For example, one class of foreign flag container vessel has posed a handling problem for pilots in several East Coast ports. These vessels are twin screw, with controllable pitch propellers and each has a single rudder. At harbor speeds they have been difficult to steer, especially in turns. Perhaps more consideration of maneuvering during the design phase of this vessel would have minimized the problem.

* CRG ACCIDENT RATE

The rate at which tankers larger than 100,000 DWT have been involved in CRG accidents has steadily declined since 1969. The design of tankers since then has not changed. This suggests that the Waterway Transportation System has become more accommodating of these large ships as experience with them is gained. While the accident rate has declined, recent casualties such as the collision between the 212,000 DWT AEGEAN CAPTAIN and the 280,000 DWT ATLANTIC EMPRESS on July 19, 1979, show that the problem has not been completely solved.

* TESTING MANEUVERABILITY

Three ways to test and evaluate tank vessel maneuvering and devices were investigated: model scale, full scale, and computer simulation (mathematical modeling). All were found valid and used to some degree in the study. Fast time computer simulation was the most flexible and inexpensive and therefore was the most widely used. Real time simulation, the most sophisticated form of computer simulation, was used in the tugboat evaluation to validate the fast

time computer model. Real time simulation has unique capabilities to evaluate those aspects of maneuvering involving human behavior, but these capabilities have not yet been fully utilized. Fast time computer simulation will be a primary tool in future maneuvering studies.

* MANEUVERING DEVICES

The study showed that maneuvering characteristics can be affected by the addition of devices. A summary of the changes to the maneuvering and stopping ability of the 280,000 DWT tanker that was used in the simulation is shown in Table 14. The results are for shallow water and maximum speed of 8 knots, both of which are realistic for harbor or offshore port approaches. The only maneuvering characteristic which was improved by more than 20 percent when a device was added, was the accelerating turn, which had an improvement of 38 percent using a bow thruster. Because the original ship's turning ability in the accelerating turn is excellent, a 38 percent decrease in advance is only slightly more than the width of the ship. None of the devices improved the course changing ability and only two devices, the twin screw/twin rudder and steerable Kort nozzle, affected both turning and stopping ability. Not all the devices shown in Table 14 are available for installation on large tankers. Steerable Kort nozzles and active rudders have not been developed for large ships.

* MANEUVERING TECHNIQUES

Several techniques for improving the maneuvering characteristics of large tankers were examined. Most promising were new ways to use tugs and slower approach speeds. Tugboat utilization strategies such as tug escort and tug assistance, including braking tugs and rudder tugs at harbor speeds were shown to be effective ways to improve the maneuvering and stopping of large tankers. Slower approach speeds give the shiphandler the option of increasing thrust in a potential accident situation. This produces the ship's best maneuvering condition.

* MANEUVERING AND CRG ACCIDENTS

Since some devices can increase the maneuvering and stopping ability of large tankers somewhat, should they be installed? The study initially narrowed the scope of the examination from that of the overall CRG risk to the inherent maneuverability of tankships. For this study to be complete maneuverability must be put back into the overall CRG situation. One question asked at the beginning of the study was, what effect will changes to maneuvering and stopping ability have on risk of CRG accidents? At this time there is no answer because there is no method or mathematical model to use which can assimilate all the pieces of the CRG situation. In the past few years, efforts have been underway both within the Coast Guard and the Maritime Administration to put together such a model. While some creative and interesting results have

Table 14 - Summary of Effect of Devices on Maneuvering Performance of 280,000 DWT Tankship in Shallow Water

	Turning Ability		Stopping Ability	Course Changing Ability	Course Keeping Ability
	Normal	Accelerating			
Twin Screw/Twin Rudder Twin Rudder	Decrease Advance 5 %	Decrease Advance 16 %	Decrease Head Reach 20 %	No Change in Ability	Not Evaluated
Increased Astern Power (includes Controllable Prop)	No Effect	No Effect	Decrease Head Reach 16 %	No Effect	No Effect
Bow Thruster	No Change in Ability	Decrease Advance 38 %	No Effect	No Change in Ability	No Effect
Steerable Kort Nozzle	Decrease Advance 16 %	Decrease Advance 15 %	Decrease Head Reach 18 %	No Change in Ability	Not Evaluated
Active Rudder	No Change in Ability	Decrease Advance 7 %	No Effect	No Change in Ability	Not Evaluated

been achieved, a workable tool is a long way off. Work will continue in this area, but there is little hope of a validated model in the next few years.

* CONGRESSIONAL MANDATES

The problem of accidental pollution which results from large tank vessels with less than adequate maneuvering and stopping ability must be addressed, but the tools necessary to satisfactorily do this are not available. Devices improve maneuvering, but not significantly. Tankers with these devices cost more than those without them. The dilemma is not new. It has been around since July 1972 when the Ports and Waterways Safety Act (PL 92-340) was passed. That law required the Coast Guard to:

> "...begin publication as soon as practicable of proposed rules and regulations setting forth minimum standards of design, construction, alteration, and repair of the vessels... Such rules and regulations shall, to the extent possible, include but not be limited to standards to improve vessel manevering and stopping ability and otherwise reduce the possibility of collision, grounding or other accident..." (emphasis added)

The requirement remains in the Port and Tanker Safety Act of 1978 (PL 95-474).

* IMPLEMENTING THE LAW

Until now the Coast Guard has not proposed rules in this area, because rules did not appear justified. The Final Environmental Impact Statement supporting Regulations for Tank Vessels Engaged in the Carriage of Oil in Domestic Trade sums up the previous Coast Guard position when stating why improvements in maneuvering and stopping ability were not included in the regulations. It states:

> "Improvements in Maneuvering and Stopping Ability
>
> Requirements for various construction features and equipment intended to improve vessel maneuvering and stopping ability (and thus reduce the possibility of an accident) have been rejected as part of these proposed regulations for the following reasons: such requirements are not included in the international standards in the 1973 Marine Pollution Convention; there are unresolved questions concerning their effectiveness in reducing accidents which must be cleared up before regulations are published; and the features and equipment available improve maneuvering and stopping ability of large tankers only marginally."

The situation is no different today. The same thing might be said five years from now. It is possible that no one will ever be able to predict with confidence the degree that certain devices will reduce the risk of CRG accidents. The question becomes, is there another way to address maneuvering and stopping ability of tank vessels? The answer is "yes."

This study has shown that tankers can be designed so that they maneuver reliably and predictably. However there is no requirement that they do so. Designing a vessel is an iterative process which includes many compromises and trade-offs. If the naval architect does not have a definite requirement for maneuvering or stopping ability, which he does have for intact or damage stability, he is not likely to accommodate such a feature at the expense of other considerations such as lower resistance or reduced vibration. Maneuvering and stopping must be considered in the design process. Performance measures for maneuverability can be developed based on existing ships which have good maneuvering characteristics. This is similar to some of the methods used to determine intact stability criteria. There must also be a way to confirm the maneuvering characteristics, so meaningful full scale maneuvering trials for each ship in a class must be done. The nature of the performance standards and the verification trials must be developed.

Perhaps the most effective contributions to the CRG problem can be made through improved training and other methods which reduce "human error." The operator of a ship must perform many functions during port entry and harbor navigation. He must have the ability to compensate for many quirks in the waterway transportation system. But this need not include a vessel with marginal maneuvering characteristics. The vessel's captain or pilot should be able to depend on his ship to maneuver reliably and predictably, and he should be able to know that his ship possesses adequate maneuvering characteristics.

Section VIII
CONCLUSIONS

There is no method (i.e. mathematical model, accident analysis or enlightened wisdom) which provides satisfactory information to use in evaluating the potential change to accident risk as a result of maneuverability improvements. Nor is a method expected to be available in the near future. Therefore, there is no way to evaluate the effectiveness of maneuvering devices to reduce oil outflow from tank ships.

Of the devices evaluated only four, bow thrusters, twin screws, controllable pitch propellers, and increased astern horsepower, are available for commercial installation on large tankships. With the exception of the bow thruster in the accelerating turn, none of these improved turning, stopping, course changing, or course keeping by more than 20 percent.

Techniques for improving inherent maneuverability are available. The most promising techniques are the use of tugs, slower approach speeds, and turning in lieu of stopping when space permits.

Even though improvements to the inherent maneuverability of tankships can be made by the addition of devices there is no need to require a specific device.

Tank vessels of all sizes can be designed so that they maneuver reliably and predictably. However there are no national or international standards which require maneuvering or stopping ability of tank vessels to be considered in the design process.

The role that improved maneuvering and stopping ability has in reducing CRG risk has not been quantified. Other approaches, such as training and improved navigational information, which allow the shiphandler to make better decisions, and tug assistance in individual ports will most likely be more effective. Even so, the people who operate tankers should be able to expect them to maneuver reliably and predictably. Tankers should be designed to meet minimum standards for maneuverability.

Section IX
COAST GUARD ACTION

The Coast Guard will initiate rulemaking to require the maneuvering capability of new tank vessels to be addressed in the design process and measured after construction of the vessels. This requirement will most likely take the form of maneuvering performance standards based on definitive maneuvers and verified by full scale trials. The regulatory work plan for this requirement is being prepared. An Advance Notice of Proposed Rulemaking will be published to solicit a wide range of comments and ideas for implementation of this action. A regulatory analysis will be prepared. Maneuvering capabilities of existing tankships will be evaluated using the standards developed. Further action required for existing ships will be based on the results of that evaluation.

The Coast Guard will also pursue this action internationally at the Intergovernmental Maritime Consultative Organization (IMCO), where the Ship Design and Equipment Subcommittee is currently dealing with maneuverability of tankers as an item of high priority.

The Coast Guard will continue to conduct studies and sponsor research in the area of vessel maneuverability with the goal of reducing the risk of CRG accidents. Some identified study areas are:

* Tug utilization strategies.

* Mathematical simulations of vessel maneuvering (including determination of hydrodynamic coefficients).

* Maneuvering devices and techniques.

* Benefit/Cost models for devices and techniques.

Cooperative efforts with the Maritime Administration will be pursued whenever the research or study area is beneficial to both agencies.

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EXXON

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MANEUVERING TRIALS OF THE 278,000 DWT ESSO OSAKA
IN SHALLOW AND DEEP WATERS

JANUARY 1979

MARINE RESEARCH PROGRAM

REPORT BY:
C. L. CRANE, JR.

PREPARED FOR:

U. S. Maritime Administration
U. S. Coast Guard
American Institute of Merchant Shipping

REPORT BY:
EXXON INTERNATIONAL COMPANY
TANKER DEPARTMENT - RESEARCH AND DEVELOPMENT
MANAGER: P. M. KIMON
SECTION HEAD: H. D. JOHNSON

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INTRODUCTION

BACKGROUND

Interest in ship controllability has increased sharply in the last few years. While laymen mainly question the size and controllability of large tankers, experienced operators are equally concerned with the unique features affecting controllability of large containerships, liquefied gas ships and other vessels.

During the same few years, special facilities for analyzing and predicting ship controllability have developed accordingly for all types and sizes of vessels. Improvements of mathematical ship maneuvering models have resulted from accelerated work on maneuvering theory, captive model tests and calculation capabilities. Taking advantage of these developments, real-time shiphandling simulators, such as at CAORF*, have been built, permitting research studies of the interactions among the many parts of overall ship/waterway control systems, including human factors. However, most simulators are used as training devices for ships' officers and pilots. In parallel work, hydraulic models of segments of particular waterways have been built which incorporate manned self-propelled ship models. These also are now being used in both controllability studies and in shiphandler training. With these tools available, the complex relationships existing among vessel, waterway, environment, aids-to-navigation, shipboard navigation aids, operating rules and the shiphandler are now subject to study and better understanding.

Maneuvering mathematical models are based on Newton's equations of motion, and incorporate such physical factors as ship's mass and fluid forces acting on hull, propeller and rudder; together with wind forces and the influences of shallow water, channel sides and water currents [References 1, 2, 3, 4 and similar sources]. Because several of the complex factors affecting maneuvers are represented using scale model data and theories containing assumptions, it is essential that mathematical models be validated through comparison of predicted results with carefully planned and executed full-scale maneuvering trials.

Unfortunately, in the case of shallow water maneuvering, few data are available for this purpose [References 5 and 6). In view of this, and with the knowledge that the most important maneuvers of large ships such as tankers occur in shallow water, the U.S. Maritime Administration,

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*Computer Aided Operations Research Facility, located at the U.S. Merchant Marine Academy at Kings Point, New York.

U.S. Coast Guard and the American Institute of Merchant Shipping* joined together to sponsor a comprehensive shallow water maneuvering trial program in the Gulf of Mexico off Freeport, Texas. The trials were conducted under the management of Exxon International Company Tanker Department in late July and early August 1977, using the 278,000 deadweight ton turbine tanker ESSO OSAKA. Organizations assisting in the planning, execution and data processing are listed in Appendix A.

OBJECTIVES

The objectives of the trials were:

1. To develop full scale ship trial data which will provide a major improvement in the quality of simulations of ship maneuvering behavior, particularly in shallow water.

2. To develop information leading to a better understanding of model scale effects on ship maneuvering predictions.

3. To improve the data upon which the size and configuration of deepwater port safety zones are based.

4. To provide data upon which to base shiphandling maneuvering information for ships' watch keeping officers and pilots.

SUMMARY

Maneuvering trials of the 278,000 deadweight ton tanker ESSO OSAKA were made in both shallow and deep water in the Gulf of Mexico in July and August 1977. This was a cooperative effort of the U.S. Government and the American Institute of Merchant Shipping and was conducted by Exxon International Company. The objectives were to provide a major improvement in the quality of simulations of ship maneuvering in shallow water under realistic operating conditions (through better understanding of scale effects and force representations), to improve data upon which the configurations of deepwater port safety zones are based, and to improve the quality of shiphandling maneuvering information to be used on the bridges of ships.

The trials were conducted in shallow and deep waters providing 20%, 50% and 320% bottom clearance, and showed the following main results:

* See Appendix A for listing of contributing members.

With 20% bottom clearance, turning circle tactical diameter increased as much as 75% over the deep water result. With 50% clearance, the increase was less than 20%, directionally confirming earlier model predictions. The ship's checking and counterturning ability was reduced in intermediate water depth, but was increased in shallow water.

The main shallow water effect on stopping from slow speed was an increase in yaw rotation to the right as the ship came to a halt (increasing to almost 90 degrees, with 20% bottom clearance). As expected, rudder control was eventually lost during stopping with sustained astern rpm, although heading could be controlled to some extent by early rudder action. In the "controlled" stop, where desired heading had priority over stopping distance, and rpm was controlled, the heading could be maintained almost constant, although this was at the expense of significantly increased stopping distance.

Perhaps the principal finding of the trials, in terms of maneuvering safety, was that steering control could be maintained in all three water depths at speeds as low as 1.5 knots, even with the engine stopped. This was demonstrated by the coasting turns and coasting Z-Maneuvers; i.e., checking and counterturning ability was preserved down to this slow speed in the coasting Z-Maneuver. Accelerating turns quantified the advantage of "kicking ahead" with the engine to expedite a turn from stopped condition. The coasting maneuvers and the accelerating turns, taken together, confirmed what is already known by good shiphandlers; i.e., that maneuverability is improved when rpm is quickly increased, and reduced when rpm is rapidly decreased. Because of this, a prudent shiphandler will navigate in tight quarters at the slowest safe speed. Then, if required to increase speed he will gain control, rather than risk losing it if required to slow down.

Other trial data covered the effects of speed of approach, propeller asymmetry and water currents. Very precise readings of selected additional maneuvers were also made for use in researching "systems identification" methods for determining hydrodynamic coefficients of the mathematical maneuvering model.

In general, the trial program showed that, by combining facilities and talents, industry and government could work together to produce fruitful results aimed at improving navigation safety and protecting the environment.

TRIAL PREPARATIONS

SHIP SELECTION

A very large crude carrier was selected for the maneuvering trials, recognizing the expected important model to ship scale effects due to

large differences in Reynolds numbers (reflecting large differences in ratios of fluid inertial to viscous forces) and the modern and extensive navigation equipment found aboard VLCCs, often including double-axis doppler sonar speed sensors. The latter was useful as part of the trial instrumentation. Other points in favor of selecting a VLCC were the anticipated construction of deepwater ports in the coastal waters of the United States, the large worldwide population of VLCCs and the concern within some segments of the public over the ability of large single-screw VLCCs to maneuver reliably and predictably, especially in shallow water.

ESSO OSAKA satisfied all these requirements, and had the additional advantage of being scheduled for lightering discharge in the Gulf of Mexico, and having had a hull cleaning and painting only three months prior to the trials. Principal characteristics and sketches are presented in Appendix B.

TRIAL AGENDA

The trial agenda shown in Table 1 was designed to efficiently obtain information on normal operating requirements, ship response in event of propulsion breakdown, and model-ship scale effects in the linear and nonlinear motion ranges.

Planning discussions were held among project sponsors and hydrodynamic and ship control experts. The water depths that were chosen provided water depth to draft ratios of 1.2 (shallow), 1.5 (medium) and greater than 4.2 (deep). The appearance of the ESSO OSAKA's cross-section in these depths is sketched in Figure 1.

TRIAL SITE SELECTION

Factors entering the selection of the shalow and medium depth maneuvering trial sites included the needs for acceptable water depths, depth gradiants and bottom smoothness. In addition, low water currents and high probability of good weather with low winds, waves and swell were sought, as were low vessel traffic, fishing effort and naval activity. Finally, a satisfactory location for trial vessel availability and logistical support were required.

The selection process was in two phases, covering a literature search of documented information from government, industry and academic sources, followed by a field confirmation of water depth, current and sea floor topography by precision survey. This work, decribed more fully in Appendix C, resulted in selection of very satisfactory shallow, medium

TABLE 1   TRIAL AGENDA

TYPE OF MANEUVER OR CALIBRATION RUN	SPEED OF APPROACH TO MANEUVERS, KNOTS		
1. MANEUVERS	DEPTH/DRAFT 1.2 SHALLOW	DEPTH/DRAFT 1.5 MEDIUM	DEPTH/DRAFT 4.2 DEEP
Turn, port, 35°L rudder	5, 7	7	7
Turn, stbd, 35°R rudder	5, 7	7	7, 10
Turn, accelerating - 35° R rudder	0+	0+	-
Turn, coasting - 35° R rudder	5	5	5
Z maneuver, 20/20	7	7	7
Z maneuver, 20/20 coasting	5	5	5
Z maneuver 10/10	7	7	7
Biased Z Maneuver	7	7	7
Spiral	7	7	7
Stop, 35°L rudder	3.5		3.5
Stop, 35°R rudder	3.5	3.5	3.5
Stop, controlled heading	3.5	-	3.5
Stop, steering for - constant heading			3.5
2. CALIBRATION RUNS			
Speed/rpm, taken during steady runs prior to chosen maneuvers	3.5, 6, 8.5	5, 7.5	7, 10
TOTAL RUNS	17	12	15

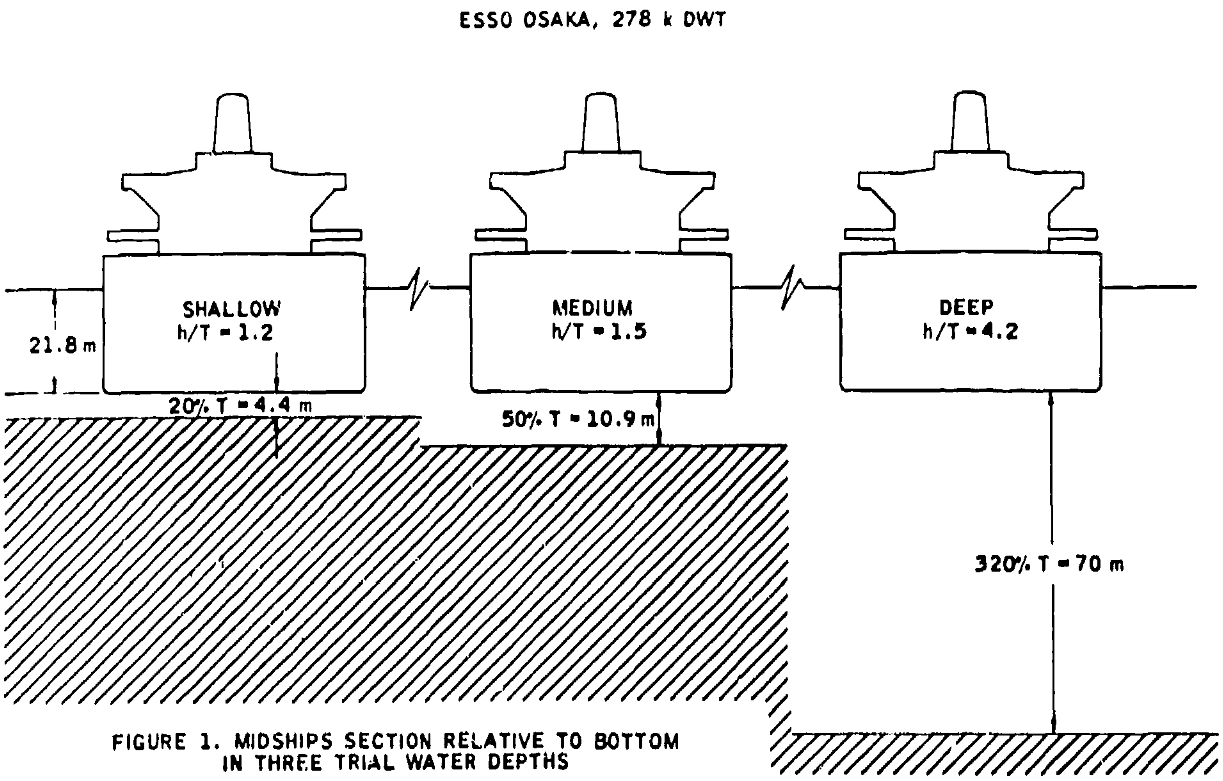

FIGURE 1. MIDSHIPS SECTION RELATIVE TO BOTTOM IN THREE TRIAL WATER DEPTHS

and deep water trial sites in the Galveston area of the western Gulf of Mexico. The area is depicted on chart segments in Appendix Figures C-1 and C-2.

MEASUREMENTS

Ship instrumentation design, installation and monitoring was provided by the Full Scale Trials Branch of David W. Taylor Naval Ship R&D Center (DTNSRDC). AMETEK, Straza Division, modified the ship's existing double-axis sonar doppler docking and navigation system to obtain precision bottom clearance information. Decca Survey Systems, Inc. separately provided ship position information.

Most trial measurements taken by DTNSRDC were from existing ship's systems in the wheelhouse with careful calibrations, as described in

Appendix D. Test instrumentation installation commenced six days prior to the trials while the ESSO OSAKA was discharging Persian Gulf crude oil into smaller lightering vessels at a position about 50 miles south of Galveston, Texas.

Water current meters were fixed to their moorings by Sippican oceanographer/divers as soon as possible after arrival of the ESSO OSAKA in each trial area and they were removed shortly before departure. Current speed and direction were automatically recorded at 9.1m (30 ft) and 21.3m (70 ft) depths at each mooring location are marked on the figures of Appendix E. The measurement system and recorded data are presented in parts of Appendix E which are paraphrased from Sippican's report (Reference 9). In addition a portable profiling current meter was used to obtain local current and temperature profiles versus depth at several locations, as also reported in Appendix E.

The following quantities were measured:

Automatically Recorded:

Position, by Decca Survey Systems (Antennae on radar mast)

Ship's heading and rate of turn

Ship's longitudinal and lateral speed components, at bow and stern locations of sonar doppler transducers

Bottom clearance at location of stern sonar doppler transducer

Wind direction and speed

Rudder angle

Propeller rpm

Water current direction and speed at two depths at two different locations adjacent to each trial site (Sippican's moored current meters)

Time

Measured and Recorded by Ship's Engineers:
(On file with Exxon International Co., R&D)

High and low pressure turbine steam pressure and temperature

Condenser vacuum and sea water temperature

Propeller shaft torque, horsepower and rpm

Time

Measured and Recorded by Oceanographer/Divers:

Water current speed, direction and temperature vertical profiles by a hand operated profiling current meter; periodically at given stations.

Periodically Measured and Recorded by Trial Director and Ship's Crew:

Vessel drafts, forward, amidships and aft, and heel angle

Wave height, period and direction (estimated)

Visibility

Visual observations of waterflow, wave making, etc.

U.S. COAST GUARD SUPPORT

Coast Guard support was received through Headquarters staff, Commander Eighth Coast Guard District staff, and from officers and crews of the C.G. Cutters DURABLE (210 Foot Medium Endurance Cutter), POINT MONROE (82 Foot Patrol Boat), and BLACKTHORN (180 Foot Buoy Tender).

Support included publication of a Notice to Mariners, special notices to fishermen and contacts with fisheries experts. Immediately prior to trials, the BLACKTHORN assisted in establishing the Sippican-prepared current meter moorings at two stations bordering each trial site. The Cutters DURABLE and POINT MONROE alternated patrol duties throughout the trial, and assisted the oceanographer/divers in locating and successfully guarding moorings and current meters against theft or damage. Birds-eye view photographs of the maneuvering ESSO OSAKA were taken by a C.G. patrol aircraft from Air Station Corpus Christi on the first day of trials.

TRIAL PROCEDURES

PRELIMINARY

Prior to entering the trial areas, the ESSO OSAKA discharged cargo and ballasted to a draft of 21.79 meters (71.5 ft.), fore and aft. Decca

Hi-Fix receivers were carried to the ship by launch, tracking the launch's position from a known location to preserve lane counts. A Coast Guard patrol cutter preceded the ESSO OSAKA into the shallow water sites, warning away fishing boats and providing safety assistance to the oceanographer/ divers as they fixed current meters to previously set moorings. The 2 x 5 mile shallow water trial site was entered via a surveyed access lane. The ESSO OSAKA then made a slow run along the shallowest side while the master verified minimum surveyed water depths.

CALIBRATION RUNS

A series of speed versus rpm calibration runs was completed prior to conducting the maneuvering trials at each site. These were required to allow equilibrium ship speed and propeller speed to be set quickly on approach runs within limited trial area dimensions. Each calibration point required three straight trial runs at the given rpm in alternating directions.

As expected, the resulting speed/rpm calibrations differed according to water depth under the ship. For example, at 35 rpm the ESSO OSAKA attained a water speed of 6.55 knots at the deep water site, 6.25 knots at the medium water depth site and 5.90 knots at the shallow water depth site. Calibration curves developed from these runs are shown in Figure 2.

TRIAL RUNS

Most of the maneuvering runs were preceded by a minimum of two minutes steady approach during which baseline data were obtained. When the execute command was passed to the helmsman, a mark was entered on the recording medium to indicate the precise time of execution. Data collection then continued at two second intervals until the end of run.

Several of the data channels, such as rpm and rudder angle were continuously monitored via digital displays in order to facilitate the approach and execute procedure. The progress of each test was monitored by the printout of all data channels at 40 second intervals.

Because of the limited trial site dimensions, it was necessary to maximize acceleration to achieve desired speed and rpm approach conditions. This was usually done by accelerating at maximum maneuvering power on a parallel and reciprocal course from the desired approach, turning 180 degrees near the end of the area and continuing the acceleration until approach speed was reached. The equilibrium rpm was then set using the feedback control and the "steady" approach commenced. Speed through

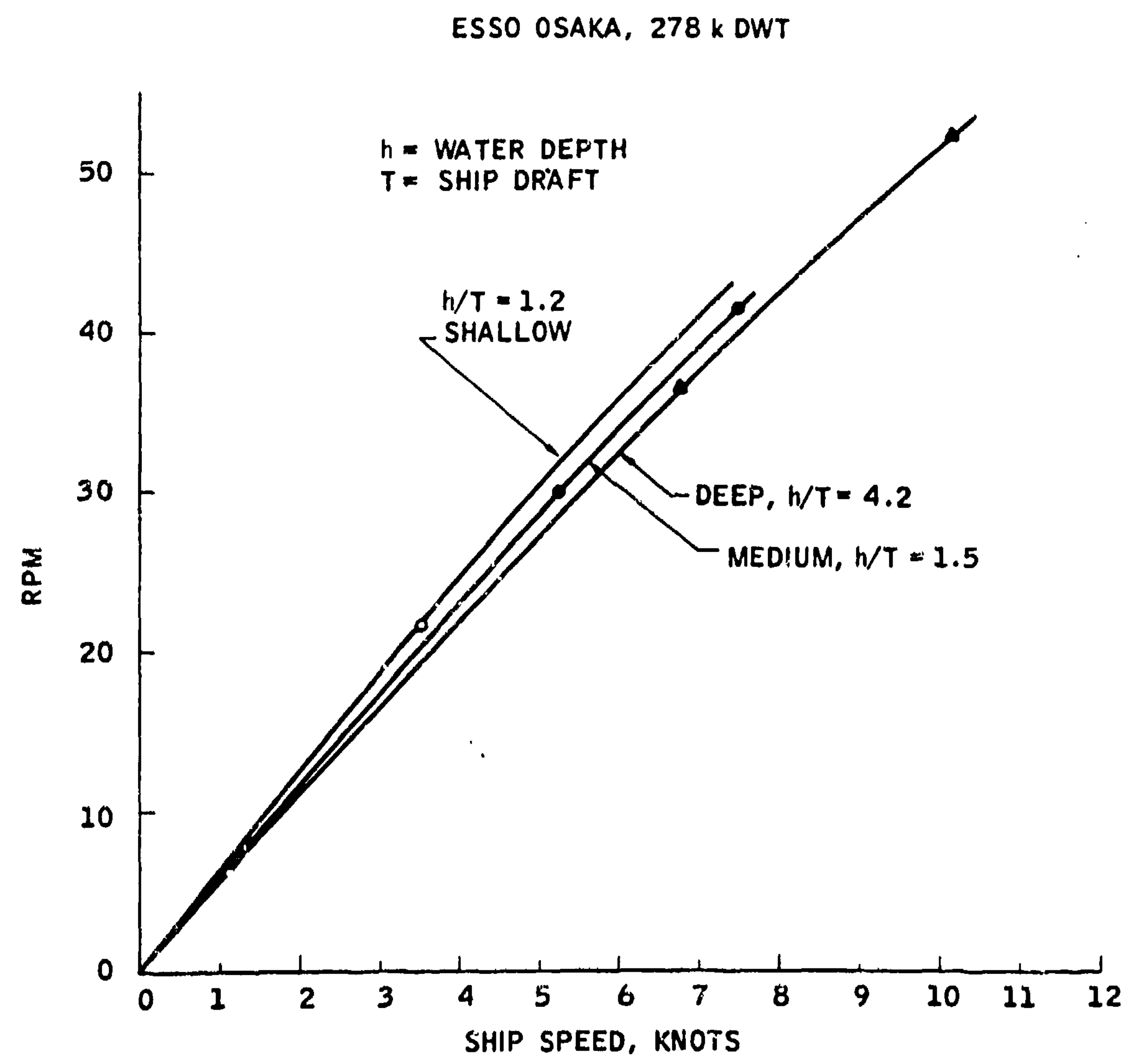

FIGURE 2. SPEED VS. RPM CALIBRATION CURVES
IN THREE WATER DEPTHS

the water was estimated by correcting measured speed-over- , ound for longitudinal drift using whatever local water current data was available at that moment.

The sequence of maneuvering runs was chosen for maximum efficiency by linking runs together with the help of pre-trial simulations. These pretrial studies were made by Hydronautics Inc., and sponsored by SNAME.

Other steps taken to avoid delays included making accelerating turns from dead-in-the-water as the first trial in the morning after drafts were read and the anchor heaved in. Stopping trials were usually made when coming to anchor at night. Except on a few occasions, the ship was not otherwise stopped.

Conventional turning circle, stopping and Z-maneuver trials followed well established procedures (Ref.'s 10 and 11) and will not be described in detail here. Definition diagrams of trial maneuvers are provided in Figures 3 and 4. However, the accelerating turn, coasting turn, stopping while steering for constant heading, stopping with controlled heading, coasting Z-maneuver, spiral test and biased Z-maneuver all require some comment.

Accelerating Turn This trial begins from dead-in-the-water. The rudder is set to 35 degrees and the engine simultaneously ordered to 55 rpm ahead. The result is a turning path tighter than with the conventional turn.

Coasting Turn The coasting turn is similar to a conventional turning circle, except that the engine is ordered stopped at the instant the initial rudder execute command is given. Due to the initially slow approach speed and ship slowdown in the maneuver, it was not practical to continue this maneuver through more than a partial turn. Modified performance measures used are discussed under "RESULTS".

Stopping While Steering for Constant Heading This is a conventional stopping maneuver with given astern rpm, except that the helmsman is ordered to hold course as closely as possible with rudder alone. In general, he will be unsuccessful after an interval as slower speed is reached. This speed depends upon the astern rpm that is ordered.

Stopping with Controlled Heading In this trial, holding the original ship's heading has priority over minimizing stopping distance. To do this the shiphandler is given freedom to control both rudder angle and engine rpm as he sees fit. It is a subjective trial depending upon the skill and training of the shiphandler. In the absence of external disturbances, rudder angle alone will not suffice for heading control as the ship loses speed with constant astern rpm. Therefore, the engine will have to be periodically stopped or even run ahead for short intervals for heading control.

Coasting Z-Maneuver This trial is similar to the conventional Z-maneuver except that the engine is ordered stopped at the instant the first rudder execute command is given. The Z-maneuver is continued until the ship's heading no longer responds to rudder. In the present trials only two or three rudder

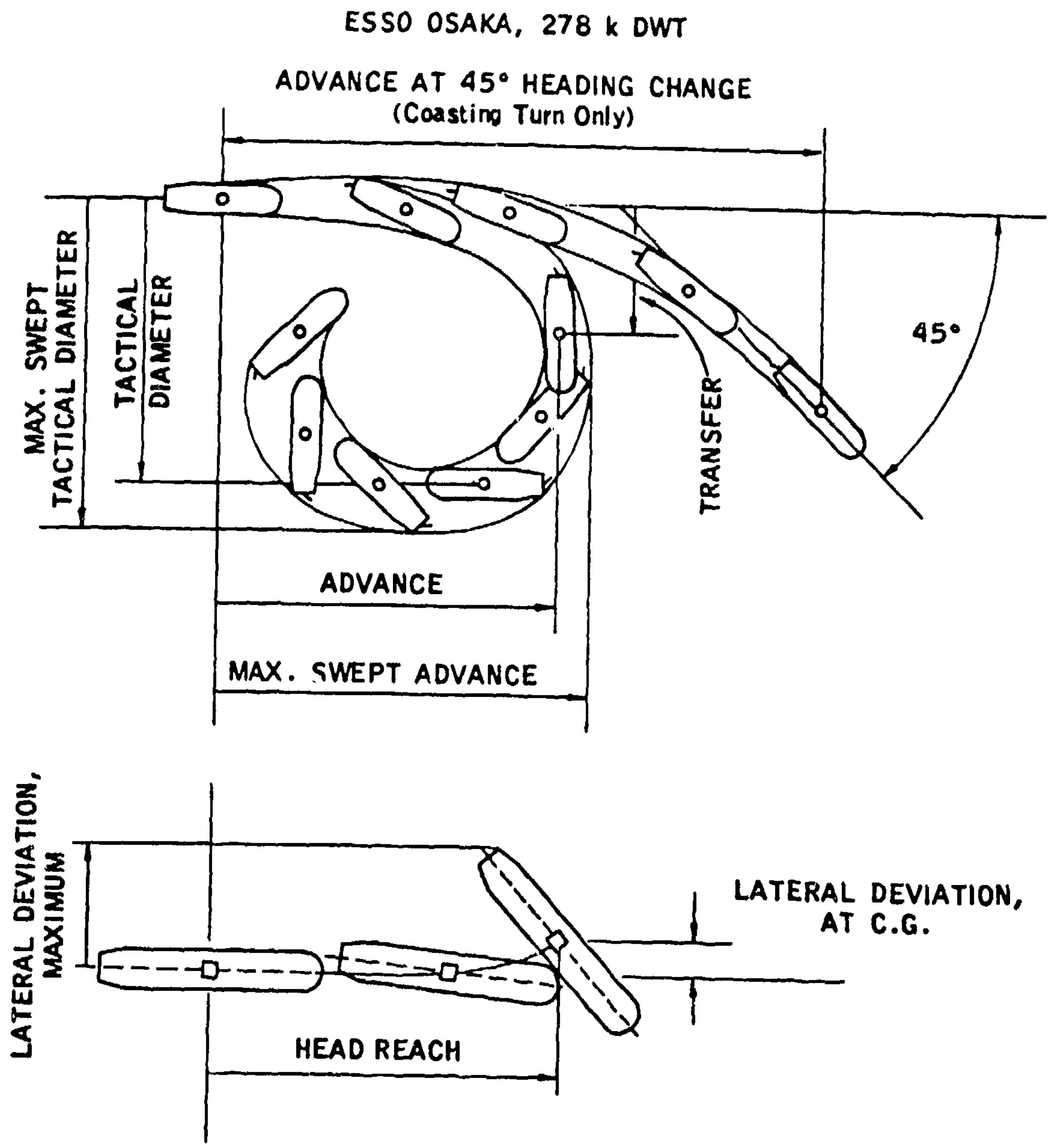

FIGURE 3. DEFINITION DIAGRAMS
Turning Circle & Stopping Maneuvers

ESSO OSAKA, 278 k DWT

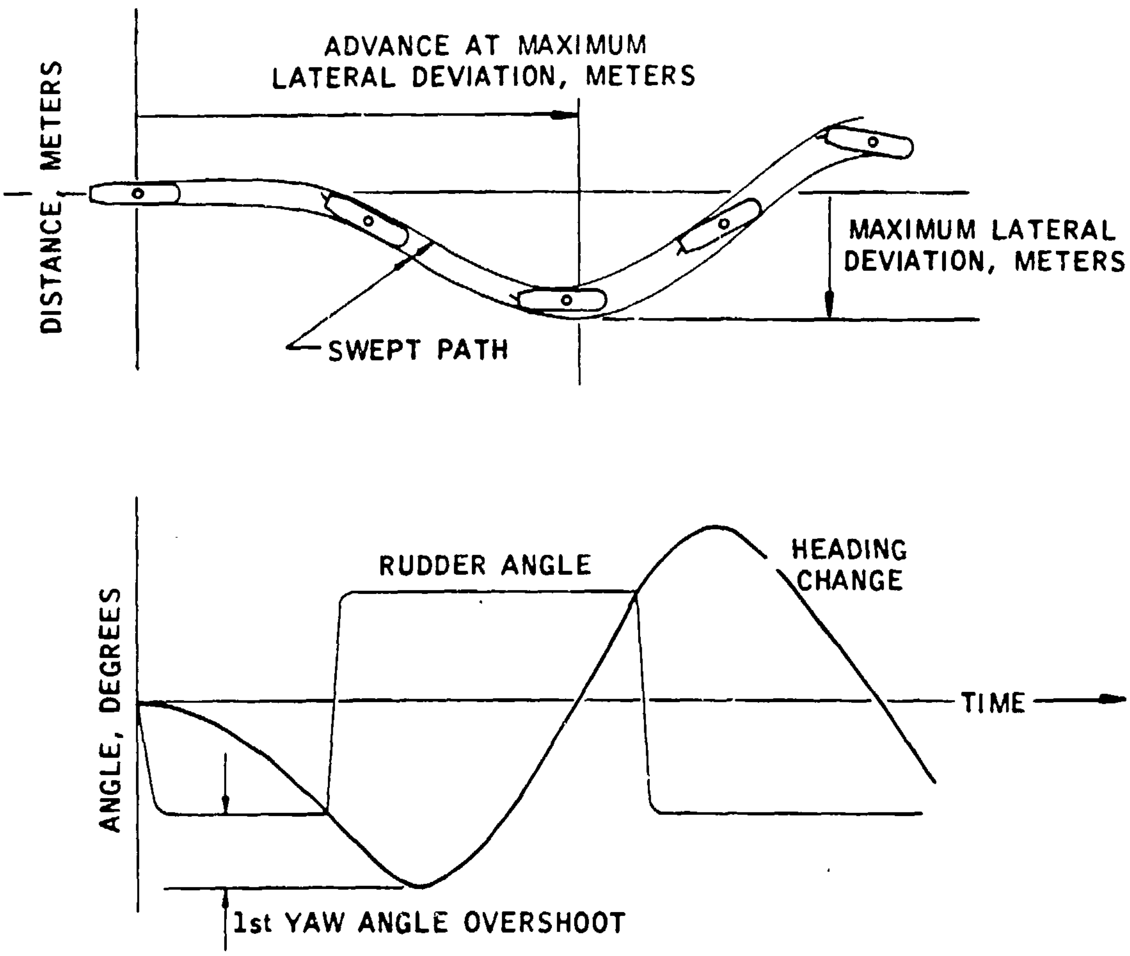

FIGURE 4. DEFINITION DIAGRAMS

Z-Maneuver

commands were made before control was lost at very slow speed. Therefore, modified performance indices were used, such as maximum lateral deviation and corresponding advance at maximum lateral deviation. These are in addition to 1st yaw angle overshoot.

Spiral Test This is a specialized maneuvering trial which provides information on dynamic stability (i.e. yaw and sway stability with controls

fixed) in a small rudder angle range about amidships (References 2, 10, 11). Only those special considerations required for the present trials are discussed here. For example, a compromise between a direct spiral and the reversed spiral was used.

In the direct spiral test, the rudder is consecutively fixed at predetermined angles, and after sufficient time to achieve steady turning, the turning rate and ship speed are recorded. To expedite the trial, which may take three hours, the reverse spiral is sometimes substituted. A skilled helmsman then steers using smallest possible rudder angle changes to achieve pre-determined turning rates (degrees per second). In the present trial, preliminary rudder commands were given by the trial director to approach the desired turning rate, after which a constant rudder angle was ordered. When turning rate and ship speed appeared constant, data were recorded. This modified procedure was used because most helmsmen are not experienced at steering ordered turning rates, and because long steadying periods would cause the limited dimensions of the 2 x 5 mile trial sites to be exceeded. Even with this procedure, it was not possible to do the spiral in a continuous run in the shallow water site.

Biased Z-maneuvers These maneuvers were made at the request of the Maritime Administration to provide transient data in the nonlinear turning range as required for systems identification work being done at MIT. MIT provided steering procedures in a sequence of rudder angles and ordered time durations. Path traces appeared as circles with somewhat flattened segments on perimeters. Data were provided directly to MIT by DTNSRDC and are not reported here.

RESULTS

GENERAL

Trial results address the effects of shallow water, engine maneuvers, approach speed, propeller asymmetry, and water currents in that order.

Time-histories presented in Appendix F were prepared for all trial maneuvers except the biased Z-Maneuver, which was performed and recorded in detail as previously described. Time-history variables include rpm, forward speed, lateral speed at center of gravity (CG), rudder angle, rate of turn, change of heading and bottom clearance. Ship speed components are corrected to "through the water", by methods described in Appendix E, together with the water current measurements.

Plots showing swept paths of the vessel are also presented in Appendix F for all maneuvers except the Z-Maneuvers, spiral tests and

biased Z-Maneuvers. Path plots, at the left in each figure, are as measured relative to ground. Plots on the right are corrected for set and drift to a nominal still water condition. Winds and seas were very mild throughout the trials and their effects are assumed negligible. See Appendix G for weather data.

[Note: Trial data printed at 2 second intervals are retained by Exxon International. Original magnetic flexible disc records are retained by DTNSRDC Full Scale Trials Branch, and data will be transferred to 8 track magnetic tape in early 1979.]

SHALLOW WATER EFFECTS

Conventional Turning Circles

The large effect of water depth on the ESSO OSAKA entering a turn is shown in Figure 5.* Turning circles were in most cases made through 540 degrees, although not indicated in path plots. Table 2 and Figure 6 report conventional measures of turning circles, and indicate that at 35 degrees left rudder, advance was reduced an average** 6% in the medium water depth compared to deep water, and in shallow water increased by about 17%.

Perhaps most significant to tanker operations are the extreme paths swept by the ship's hull. In this report, swept path indices are measured from the extension of the approach path of the ship's center-of-gravity, to the point on the hull which sweeps the widest path during the maneuver. Table 3 relates maximum swept advance and maximum swept diameter to water depth.

These data show that swept advance was reduced by an average of 8% in medium depth and increased by about 13% in shallow water, both relative to results in deep water. Maximum swept diameter increased by about 16% in medium depth and 61% in shallow water.

Transfer at 90 degree heading change increased an average of 19% in medium depth and by 88% in shallow water. Probably the most obvious water depth effect is on tactical diameter which, at 180 degree heading change, increased by 18% in medium depth and 74% in shallow water.

Taken together these results show that normal modest course-changing maneuvers of a VLCC are not greatly affected by water depth; although

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* In this report depth-to-draft ratio is designated by h/T. Shallow water was nominally at h/T=1.2, medium depth at 1.5 and deep water at h/T greater than 4.2.

** Averages of right and left hand turns.

ESSO OSAKA, 278 k DWT

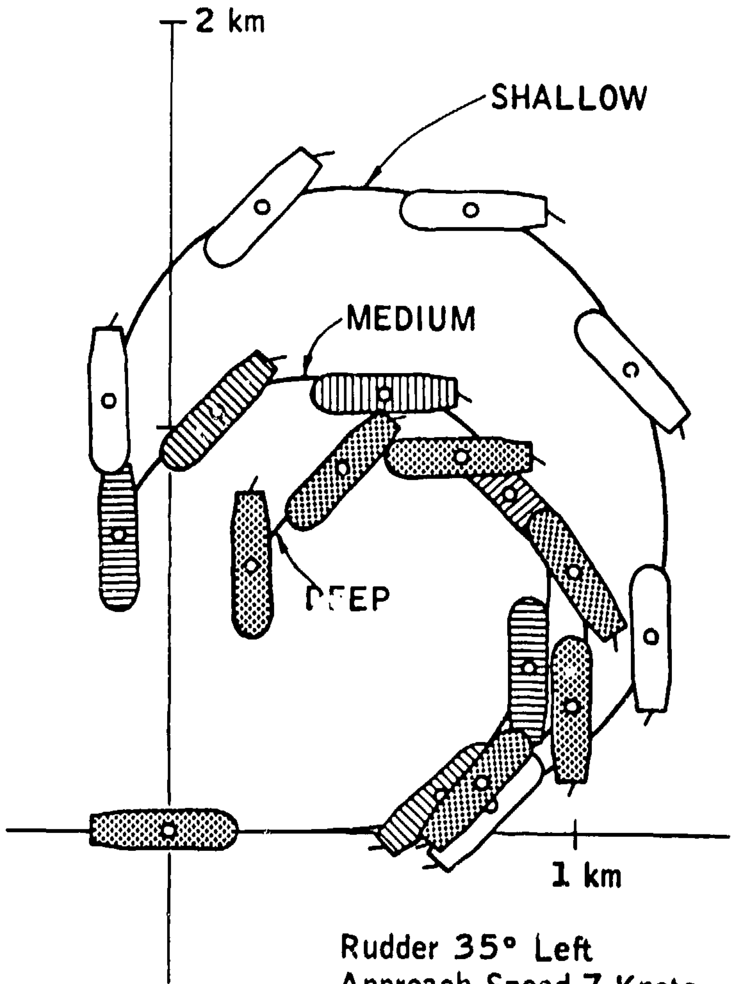


FIGURE 5. WATER DEPTH EFFECT ON TURNING CIRCLE PATHS

the infrequent 180 degree course reversal maneuver will be affected substantially.

Table 2 also shows that there is much less reduction of speed in a turn in shallow water than in medium or deep depths. At 180 degrees heading change, speed loss from approach speed in deep water was roughly 57%. In the medium depth the speed was reduced by 48% and in shallow water by 40%.

TABLE 2 TURNING CIRCLE RESULTS VS. WATER DEPTH, Expressed Using Conventional Indices

RUDDER ANGLE	DEPTH ÷DRAFT	AT 90° HEADING CHANGE							AT 180° HEADING CHANGE			
		ADVANCE			TRANSFER			SPEED LOSS	TACTICAL DIAMETER			SPEED LOSS
		m	÷L	Δ*	m	÷L	Δ*		m	÷L	Δ*	
35°Left	4.2	1005	3.1	—	310	0.9	—	35%	895	2.75	—	56%
"	1.5	915	2.8	-9%	385	1.2	+24%	32%	1075	3.31	+20%	46%
"	1.2	1190	3.7	+18%	555	1.7	+79%	26%	1565	4.82	+75%	40%
35°Right	4.2	1015	3.1	—	360	1.1	—	33%	925	2.85	—	58%
"	1.5	990	3.1	-2%	405	1.3	+13%	33%	1075	3.31	+16%	50%
"	1.2	1180	3.6	+16%	705	2.2	+96%	35%	1590	4.89	+72%	40%

- Approach speed 7 knots
- Corrected for set and drift
* % change from deep water results

ESSO OSAKA, 278 k DWT

(SEE FIGURE 3 FOR DEFINITION DIAGRAM)

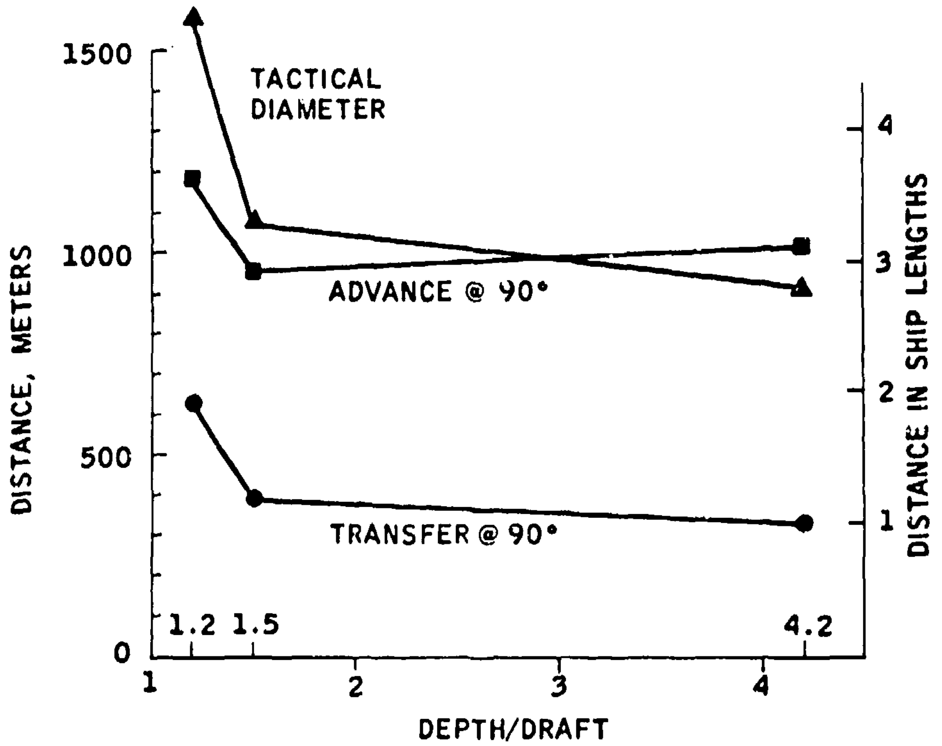


FIGURE 6. WATER DEPTH EFFECT ON TURNING CIRCLE INDICES

Approach Speed 7 Knots

Coasting Turns

An interesting characteristic of shallow water maneuvering is seen in the coasting turn. Results for the coasting turn to the right with 35 degree rudder are presented in Figure 7, which also shows the conventional deep water 35 degree rudder turn for comparison. Notice that initial turning is greatest in the medium water depth and least in deep water. In the shallow and deep cases, turning is consistently to the right, whereas in medium depth there is a slight reversal toward the end. As a performance measure for the coasting turn, we compare in Figure

TABLE 3. TURNING CIRCLE RESULTS VS. WATER DEPTH
Expressed Using Maximum Swept Path Indices

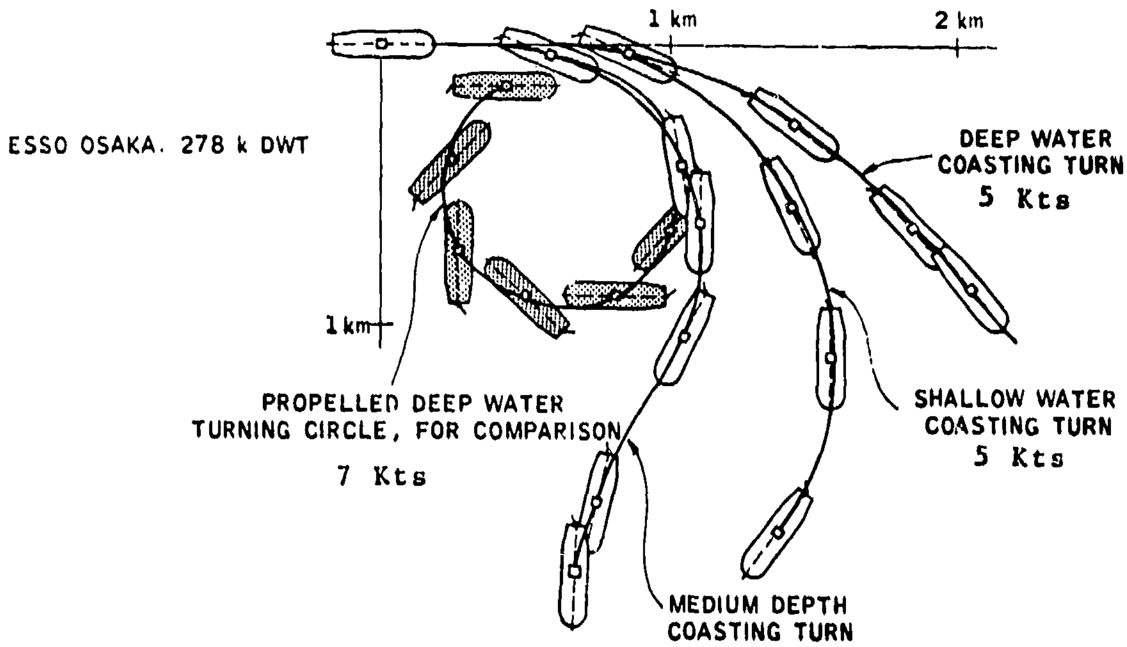
RUDDER ANGLE	DEPTH ÷ DRAFT	MAXIMUM SWEPT ADVANCE⁻			MAXIMUM SWEPT TACTICAL DIAMETER		
		meters	÷L	Δ*	meters	÷L	Δ*
35°Left	4.2	1160	3.6	—	1040	3.2	—
"	1.5	990	3.1	-15%	1190	3.7	+14%
"	1.2	1270	3.9	+10%	1690	5.2	+63%
35°Right	4.2	1100	3.4	—	1025	3.2	—
"	1.5	1080	3.3	-2%	1200	3.7	+17%
"	1.2	1280	3.9	+16%	1620	5.0	+58%

- Approach speed 7 knots
- Corrected for set and drift
* % change from deep water results

ADVANCE AT 90 DEGREES HEADING CHANGE

Coasting Vs. Powered Turn, 35 Degrees Rudder (R)

	Propelled Turn, meters	÷L	Coasting Turn, meters	÷L	Coasting/Propelled
DEEP*	706*	2.2	1906*	5.9	+170%
MEDIUM	990	3.1	1140	3.5	+ 15%
SHALLOW	1182	3.6	1616	5.0	+ 37%



*Deepwater Turn Compared At 45° Heading Change

FIGURE 7. WATER DEPTH EFFECT ON THE COASTING TURN

7 advance at 90 degrees heading change* to that in the conventionally powered turn. This shows how degradation of turning by coasting varies with water depth.

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*Compared at 45 degrees heading in deep water only, since heading did not reach 90 degrees.

In deep water, coasting caused the advance in turning at 45 degrees heading change to increase by 170%*. In medium depth coasting caused advance at 90 degrees heading change to increase by only 15%, and in shallow water it increased by 37%.

Accelerating Turns

Accelerating turns were made in both medium and shallow water depths by building up rpm from zero to about 56 ahead, beginning with ship dead-in-the-water with rudder angle 35 degrees right. As shown in Figure 8, the main water depth effect is seen in the changes in the tactical and maximum swept diameters. In shallow water the tactical diameter increased by 31% and the maximum swept diameter by 26% relative to medium depth water.

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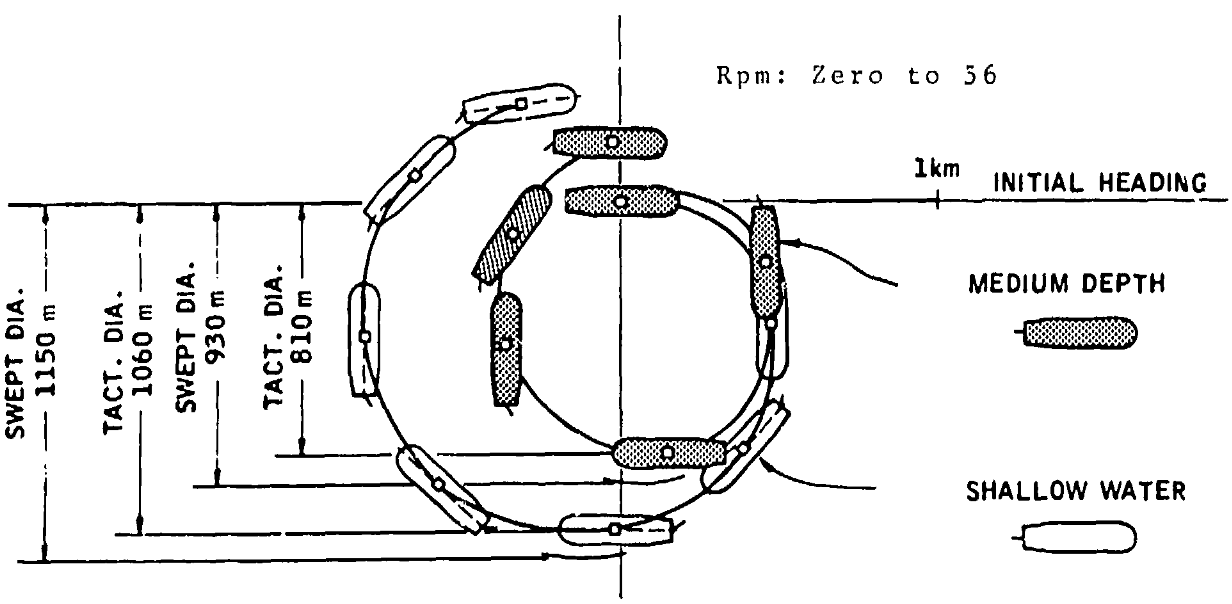

FIGURE 8. WATER DEPTH EFFECT ON ACCELERATING TURN

Shallow Vs. Medium Water Depth

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*Compared at 45 degrees heading, since heading did not reach 90 degrees.

Stopping Maneuvers

Water depth effects on stopping from slow speed are most apparent in trials made with 35 degree right rudder and engine ordered to 45 rpm astern. Figures 9 and 10 show that head reach is roughly the same in the deep, medium and shallow water depths at 520, 575 and 550 meters respectively. And as shown in the table on Figure 9, had the approach speed of the deep water maneuver been exactly the 3.8 knots of the medium and shallow maneuvers, instead of 3.5 knots, even closer results would have been obtained. The water depth effect is most strongly seen in the large heading change as the ship comes to a halt. Heading change varied from 18 degrees in deep water to 50 degrees in medium depth to 88 degrees in shallow water, all to the right.

Lateral deviation of the ship's CG from the extended trackline was small, varying from 20 meters starboard to 50 meters port to 35 meters port for deep, medium and shallow depths. Obviously, maximum swept path deviations are more pronounced, with the bow 90 meters to starboard in deep water, and the stern 200 meters to port in medium depth and 205 meters to port in shallow depth.

Z-Maneuvers

Z-Maneuvers describe relative checking and counterturning ability in maneuvers about an initial heading. Table 4 and Figure 11 provide values in the three water depths for the 20°-20° Z-maneuver with initial 7 knot speed.

TABLE 4 20°-20° Z-MANEUVER INDICES VERSUS WATER DEPTH

(Approach Speed 7 Knots)

	DEEP	MEDIUM	CHANGE*	SHALLOW	CHANGE*
1st Yaw Angle Overshoot, degrees	9.5	11.2	+18%	7.8	-18%
Maximum Lateral Deviation, meters	460	590	+28%	505	+10%
Advance, at Maximum Lateral Deviation, meters	1540	1650	+7%	1400	-9%

*Relative to deep water result.

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DEPTH ÷DRAFT	HEAD REACH				LATERAL DEVIATION			FINAL HEADING CHANGE
	Distance, meters	From V Knots	Corrected to 3.8 Kts.	Change, Rel. to Deep Water	At CG, meters	Max. meters	Location On Ship	
4.2	520	3.5	582	—	20 Stb	90S	Bow	18° Right
1.5	575	3.8	575	-1%	50 Port	200P	Stern	50° Right
1.2	550	3.8	550	-5%	35 Port	205P	Stern	88° Right

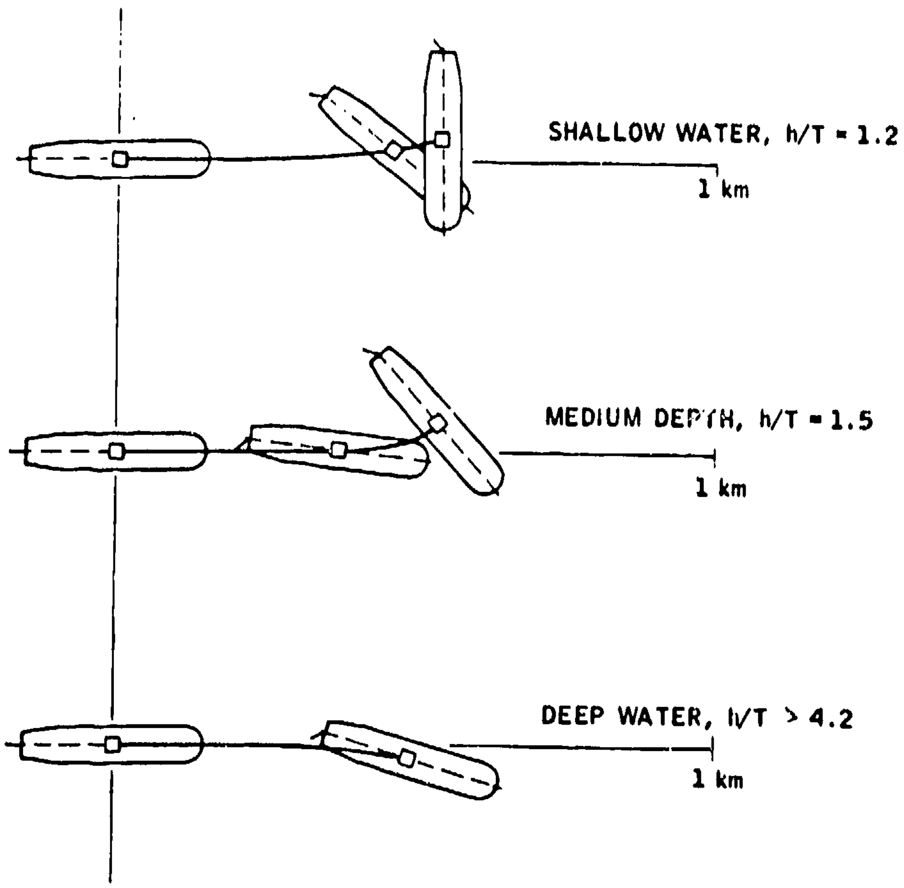

FIGURE 9. WATER DEPTH EFFECT ON STOPPING PATH
From 3.8 Knots, With 35° R Rudder & 45 Rpm Astern
(About 50% Of Available Astern Power, Ref. 9)

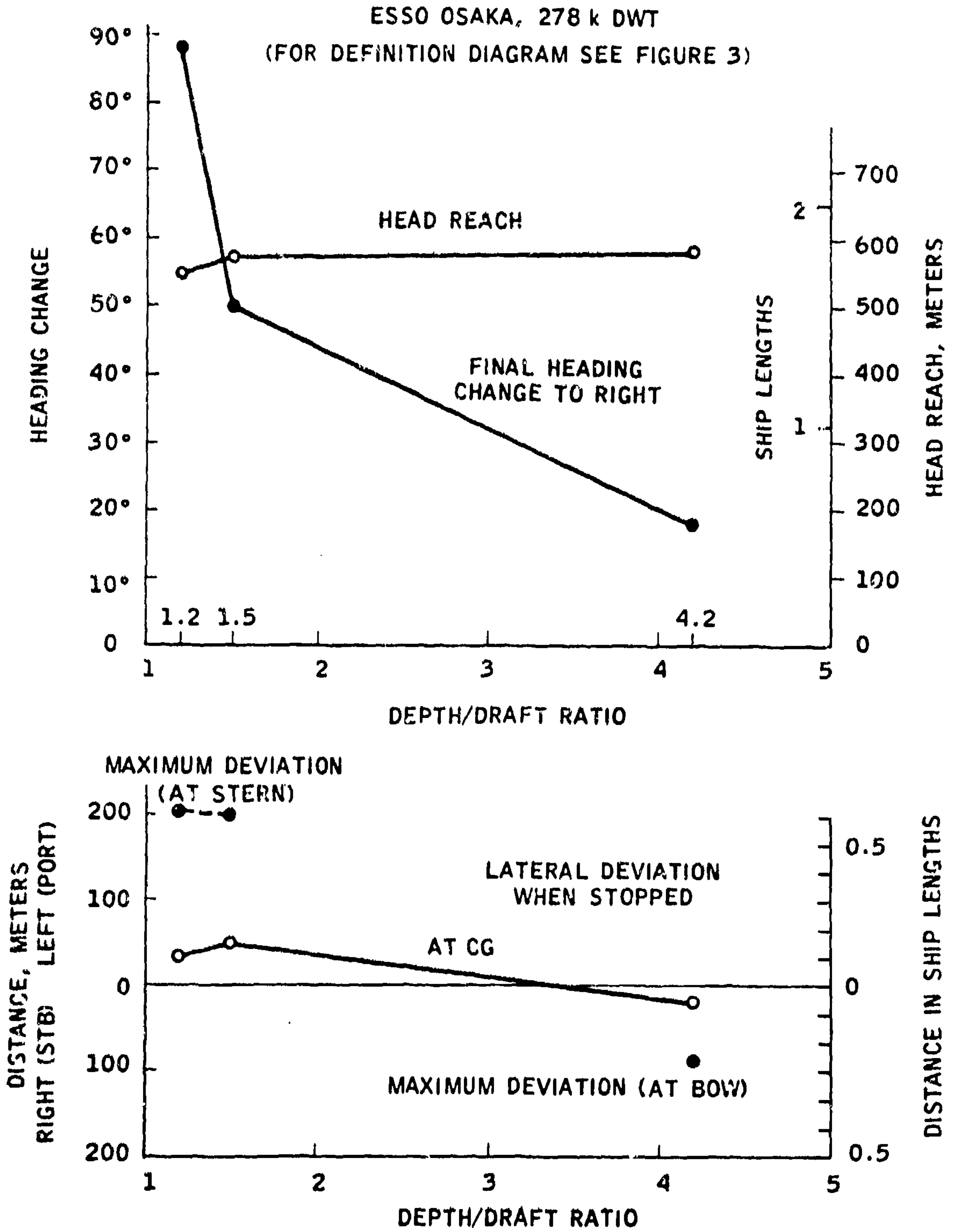

FIGURE 10. STOPPED POSITION OF SHIP AS AFFECTED BY WATER DEPTH (35° R RUDDER, 45 RPM ASTERN)

Approach Speed 3.8 Knots

For port entry type maneuvers, the 1st yaw angle overshoot and the resulting maximum lateral deviation (swept path away from original trackline) are significant. First yaw angle overshoots in the 20°-20° maneuver varied from 9.5 degrees in deep water, to 11.2 degrees in medium depth, to 7.8 degrees in shallow water. The maximum swept path lateral deviation from trackline varied from 460 meters, deep, to 590 meters, medium, to 505 meters, shallow.

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(FOR DEFINITION DIAGRAM, SEE FIGURE 3.)

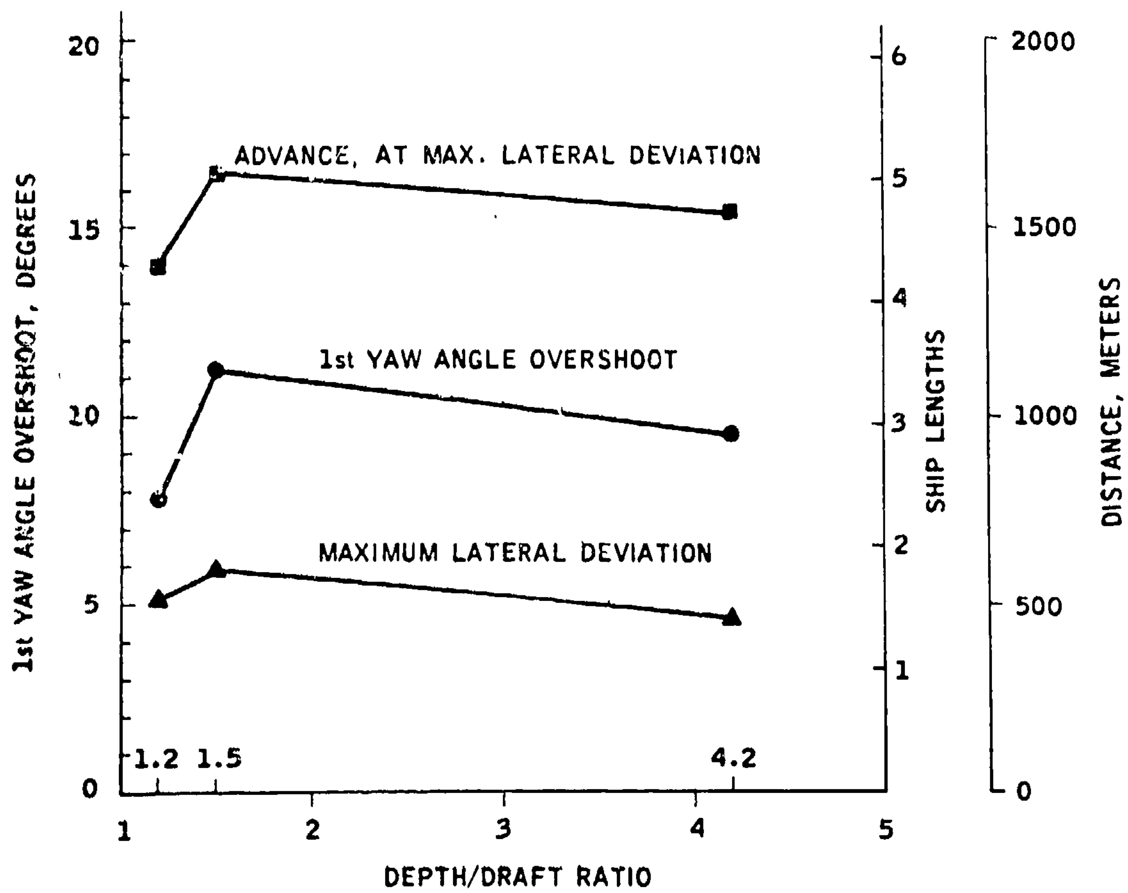

FIGURE 11. Z-MANEUVER RESPONSES VS. WATER DEPTH

(20°-20° Z-Maneuver)

7 Kts

In the 10°-10° Z-maneuvers the first yaw angle overshoots varied from 3.6 degrees in deep water to 7.9 degrees in medium depth to 6.2 degrees in shallow water; however there was some drift of rudder angles, as apparent from the time-histories in Appendix F.

Coasting Z-Maneuvers

The effect of water depth on a ship's ability to continue maneuvering without propulsion power is shown by the coasting Z-maneuver. It is also useful for determining a rough minimum maneuvering speed with engine stopped.

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	DEEP	MEDIUM	CHANGE*	SHALLOW	CHANGE*
1st Yaw Angle, Overshoot, degrees	10	20	+100%	5	-50%
Maximum Lateral Deviation, meters	615	1445	+135%	700	+14%
Advance, at Max. Lateral Deviation, meters	1795	2700	+ 50%	1905	+ 6%
Speed when Maneuver Discontinued , Knots	1.7	2.1		1.4	

* Relative to deep water result

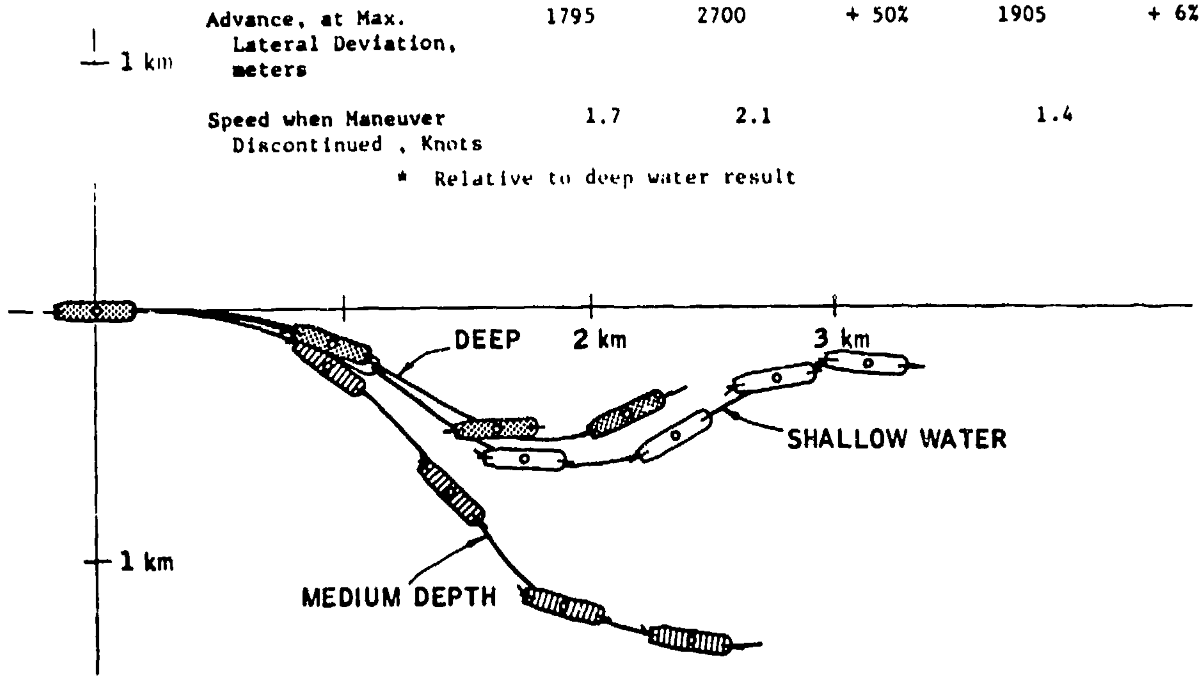

FIGURE 12. WATER DEPTH EFFECT ON COASTING Z-MANEUVER

20°-20° Maneuver, From 5 Knots

Again, 1st yaw angle overshoots, maximum lateral deviation and advance to that point are all informative. Figure 12 shows the effect of shallow water on the coasting Z-maneuver.

Spiral Test

Spiral test results provide certain technical information on steady state turning characteristics at small fixed rudder angles; i.e., in the absence of active steering. However, they provide no direct information on maneuvering or coursekeeping ability with active steering; at least not in the case of large slow vessels such as VLCCs. In fact, spiral tests are not meaningful to the ship handler, especially as they apply to VLCCs, unless unusual results are obtained from the Z-maneuver, such as abnormally large overshoots.

A main purpose of the spiral test is to determine whether the resulting turning rate versus rudder angle curve contains a "hysteresis loop", which would be associated with "dynamic instability". However, it is important to understand that the technical term "dynamically unstable", as used in these paragraphs, relates to controls-fixed stability and does not directly relate to acceptable "directional stability", with use of the rudder, which is a required characteristic of every vessel.

The present spiral tests show interesting characteristics. Records of turning rate in degrees per second are provided in Appendix H, together with working summary plots. From these, smoothed summary dimensionless plots were prepared, as shown compositely in Figure 13. Comments are as follows:

Deep water spiral test: Turning rate versus rudder angle results of Figure 13 and Appendix H suggest that the ESSO OSAKA is marginally dynamically stable in deep water; i.e. no definite "loop" resulted, even though a very minor loop might have appeared if this particular trial was prolonged beyond the 2 hours 30 minutes used.

Medium depth spiral test: Results in Figure 13 and Appendix H suggest that a narrow loop of perhaps one degree width exists, with a dimensionless height of about 0.4.

Shallow water spiral test: Results in Figure 13 and Appendix H suggest that the vessel is probably dynamically stable, and probably has no loop. This interpretation ignores some of the plotted points and is based upon:

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* Mainly in the interest of time.

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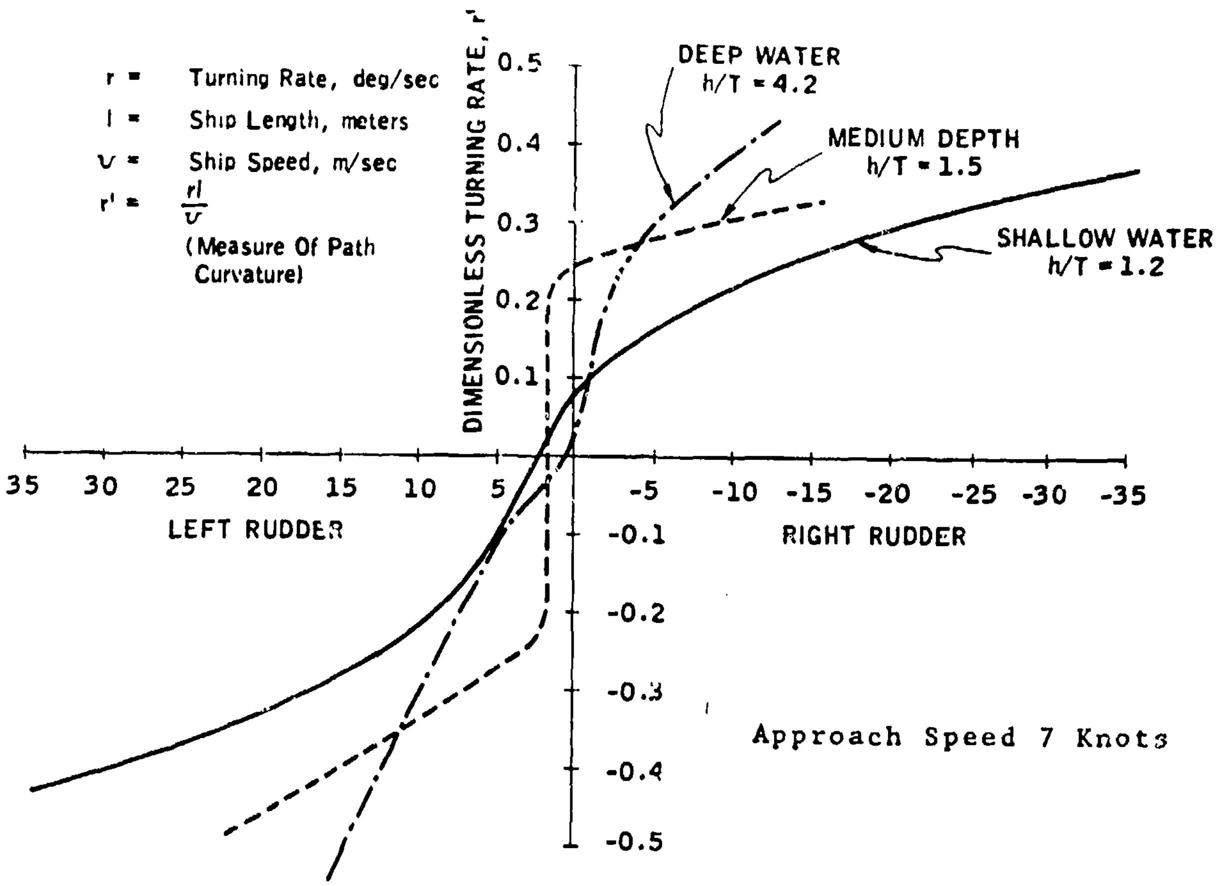

FIGURE 13. SMOOTHED SPIRAL TEST RESULTS
Dimensionless Turning Rate Vs. Rudder Angle

a. Suspicion of points just to the left of the origin in Appendix H Figure H-3 because of the limited time they could be held for steady results. This was because of the restricted size of the 2 x 5 mile surveyed "safe" trial area.

b. Problems incurred in obtaining the points near the origin in piecewise fashion for the same reason as given above.

c. The tendency suggested by all points except those just to the upper left of the origin. A dashed line for the expected actual curve has been added to Figure H-3.

Taken together, the spiral test data in the three water depths suggest marginal dynamic stability in deep water, probable small instability in the medium depth, and stability in the shallow depth. Consistency of these results with the turning circle and Z-maneuver data are considered under "DISCUSSION OF RESULTS".

PROPELLER RPM EFFECTS ON HEADING CONTROL

The effects of the use of propeller rpm on maneuvering are shown by certain turning, stopping and Z-maneuver trials.

Rpm Effects on Turning

Turning of a single-screw single-rudder ship is strongly affected by use of propeller rpm. This is clearly shown in Figure 14 for the case of water-depth-to-draft ratio 1.2. The conventional turning maneuver shown in path A is diminished when the vessel coasts with propulsion power cut off, as in path B. The accelerating turn, Path C, has a different approach condition, beginning from dead-in-the-water and building up propeller speed to about 56 rpm from the moment the rudder is deflected to 35 degrees right.

Similar rpm effect results were obtained in medium depth water, as see in Figure 15.

Coasting Versus Conventional Z-Maneuvers

The relative ability to maneuver while "coasting" is seen in Table 5, which compares the coasting condition to the conventional Z-maneuvers

TABLE 5 EFFECT OF COASTING ON 20°-20° Z-MANEUVER IN THREE WATER DEPTHS

	DEEP		MEDIUM		SHALLOW	
	Convent.	Coasting	Convent.	Coasting	Convent.	Coasting
1st Yaw Angle Overshoot, degrees	9.5	10	11.2	20	7.8	5
Maximum Lateral Deviation, meters	460	615	590	1445	505	700
Advance, at Maximum Lateral Deviation	1540	1795	1650	2700	1400	1905
Speed on Approach, Knots	7	5	7	5	7	5
Speed when Maneuver Discontinued, knots	4.5	1.7	4.8	2.1	5.1	1.4

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	PATH A Conventional	PATH B Coasting	Change*	PATH C Accelerating	Change*
Advance, at 90 degree heading change, meters	1180	1615	+37%	490	-59%
Transfer, at 90 degree heading change, meters	705	1075	+53%	375	-47%
Tactical diameter, at 180 degree heading change, meters	1590	Incomplete	—	1060	-33%

* Relative to conventional turning results

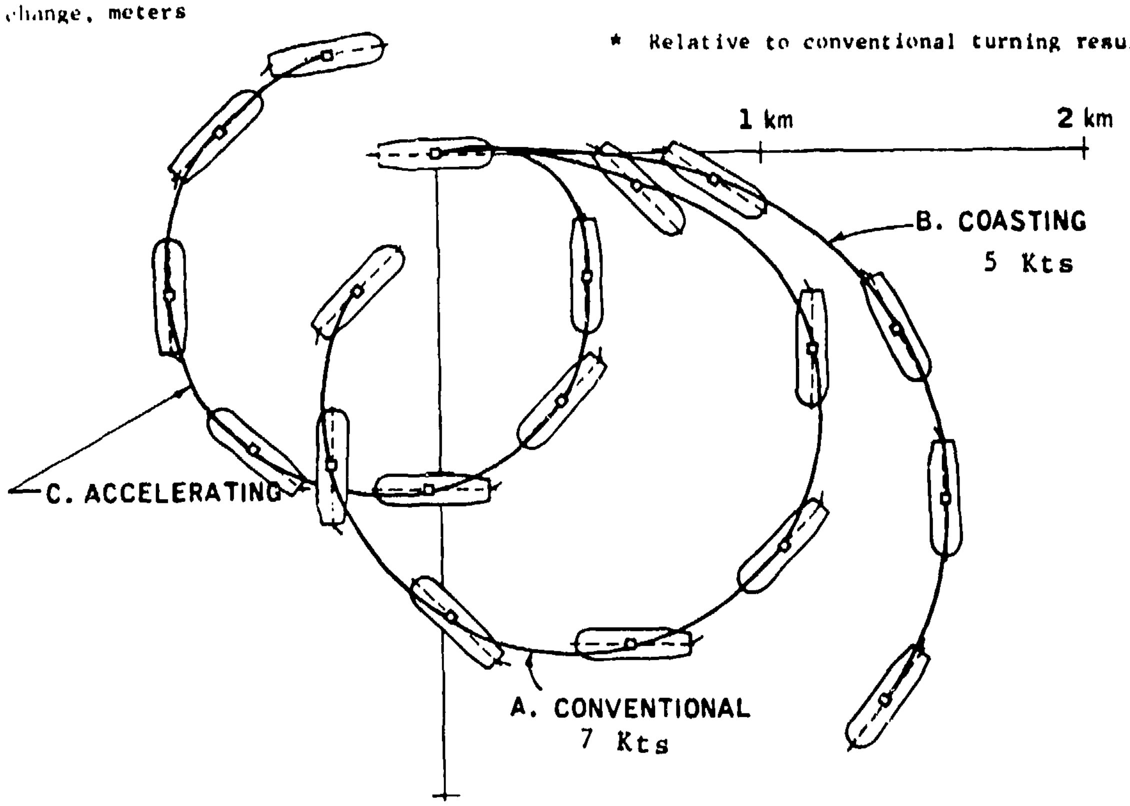

FIGURE 14. RPM EFFECT ON TURNING CIRCLE PATH, IN SHALLOW WATER
Coasting, Conventional And Accelerating Turns

of Table 4. Figure 16 shows the variations of Z-maneuver paths, coasting versus powered, for the three water depths. Figures 17 and 18 show how water depth changes the effects of coasting on Z-maneuver overshoot, maximum deviation and advance.

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	PATH A Conventional	PATH B Coasting	Change*	PATH C Accelerating	Change*
Advance, at 90 degree heading change, meters	960	1115	+ 16%	470	- 51%
Transfer, at 90 degree heading change, meters	395	615	+ 56%	190	- 52%
Tactical diameter, at 180 degree heading change, meters	1045	Incomplete	—	800	- 23%

* Relative to conventional turning results

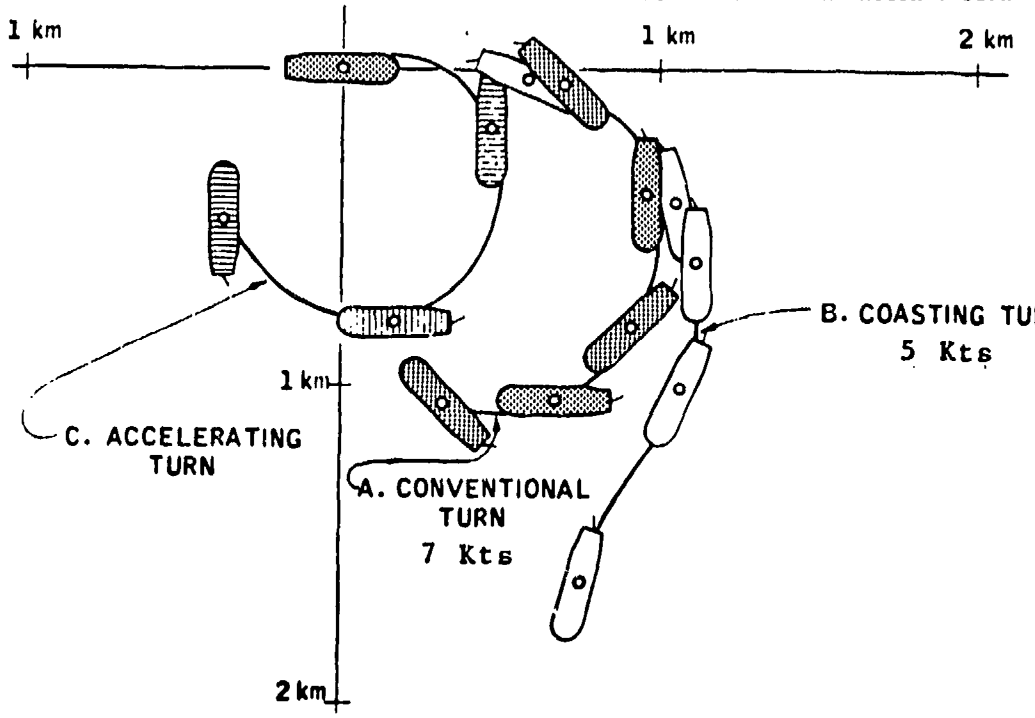

FIGURE 15. RPM EFFECT ON TURNING PATH IN MEDIUM WATER DEPTH

Coasting, Conventional And Accelerating Turns, 35° Right Rudder

EFFECT OF RUDDER AND RPM CONTROL ON STOPPING

Rudder Angle Effect

The stopping results reported under "water depth effect" were for the 35 degrees right rudder case. The effects of applying instead

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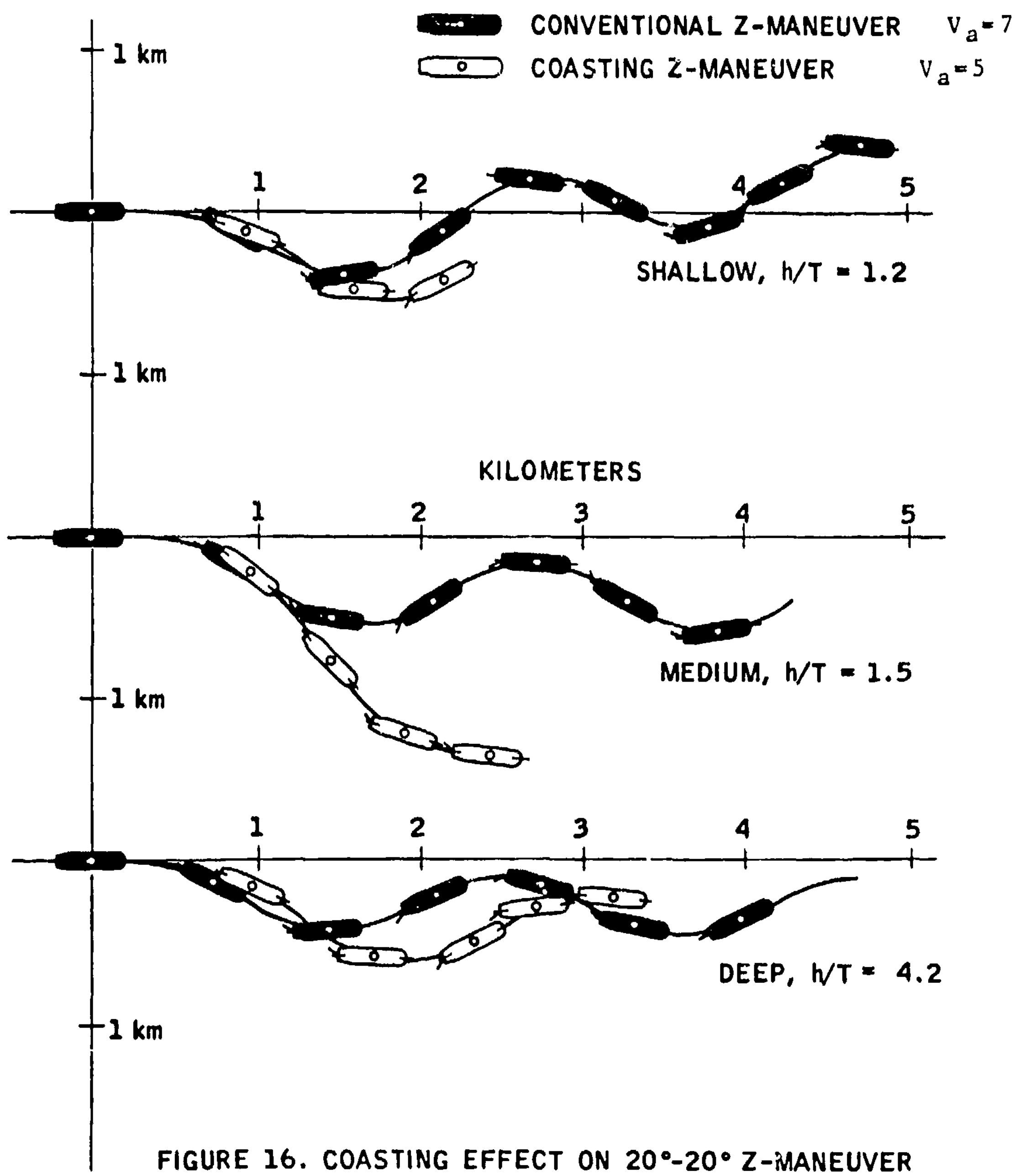

FIGURE 16. COASTING EFFECT ON 20°-20° Z-MANEUVER IN THREE WATER DEPTHS

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(FOR DEFINITION DIAGRAM SEE FIGURE 4.)

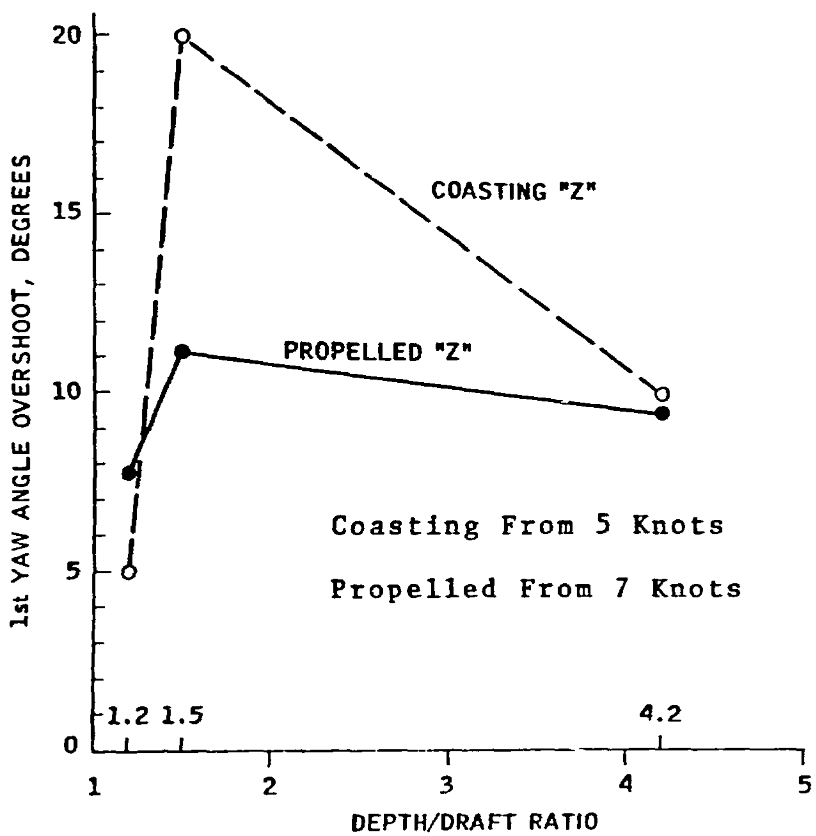

FIGURE 17. 20°-20° Z-MANEUVER RESPONSE; COASTING EFFECT ON 1st YAW OVERSHOOT, IN THREE WATER DEPTHS

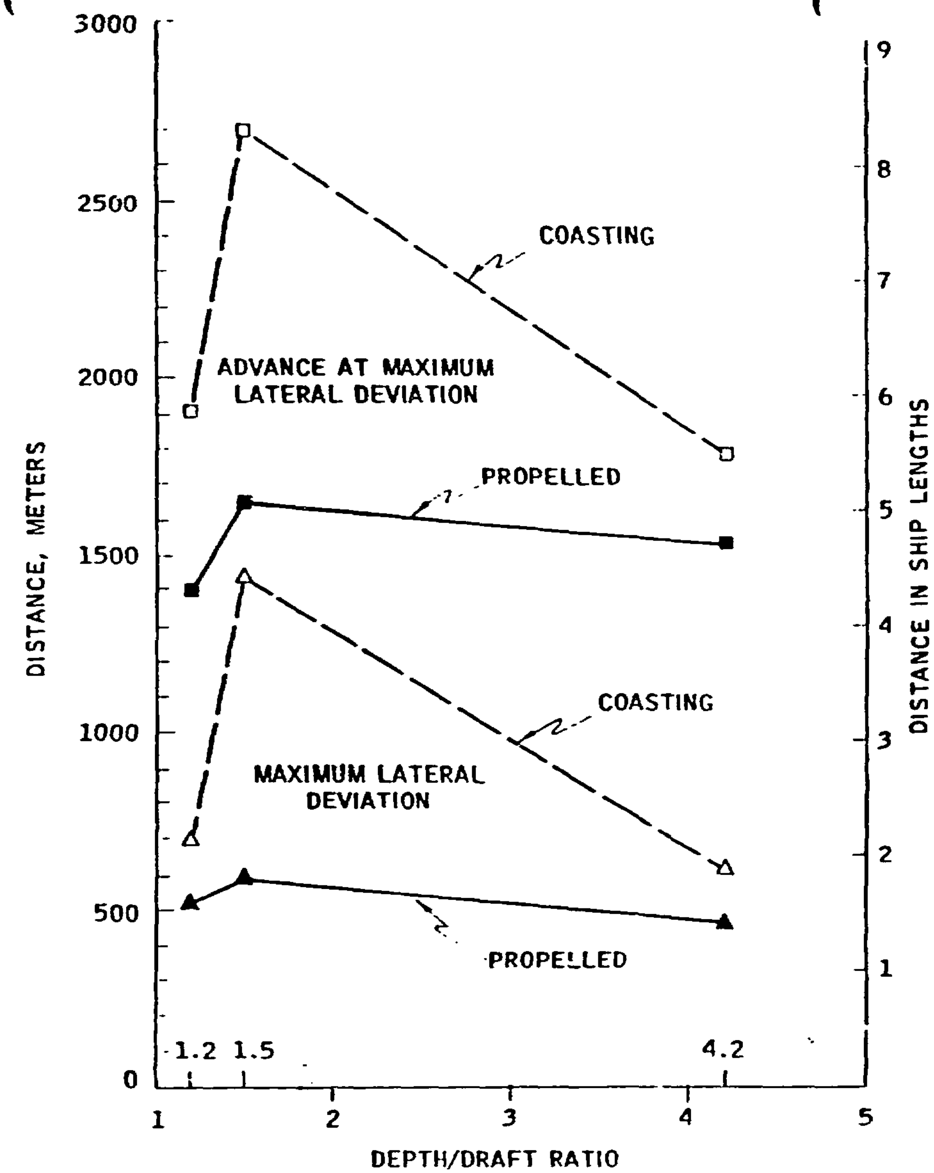

FIGURE 18. 20°-20° Z-MANEUVER RESPONSE; COASTING EFFECT ON LATERAL DEVIATION AND ADVANCE, IN THREE WATER DEPTHS

ESSO OSAKA, 278 k DWT

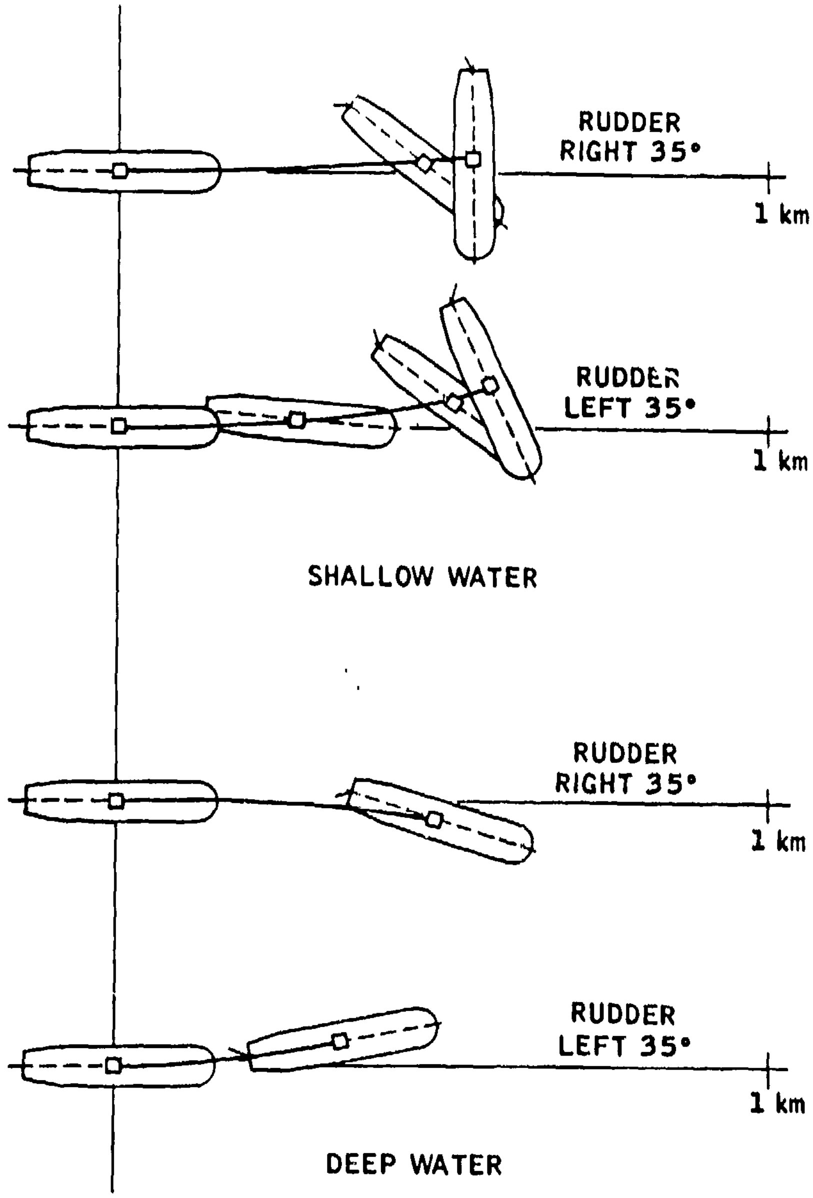

FIGURE 19. RUDDER ANGLE EFFECT ON STOPPING, IN SHALLOW AND DEEP WATER, FROM 3.8 KNOTS WITH 45 RPM ASTERN

35 degrees left rudder in the deep and shallow water cases can be seen in the combined Figure 19, with paired left and right rudder stopping maneuvers. The tendency of the astern propeller rotation to move the stern to port is clearly preponderant in shallow water, whereas rudder angle was the controlling factor in deep water.

In deep water, special trials were made to show the value of steering and rpm maneuvers for maintaining constant heading while stopping. Results are shown in Figure 20. The base case was a simple stopping maneuver with engine ordered 45 rpm astern and rudder ordered 35 degrees right (top of Figure 20), from an approach speed of 3.5 knots. Next, steering for constant heading was attempted, with engine ordered to a constant

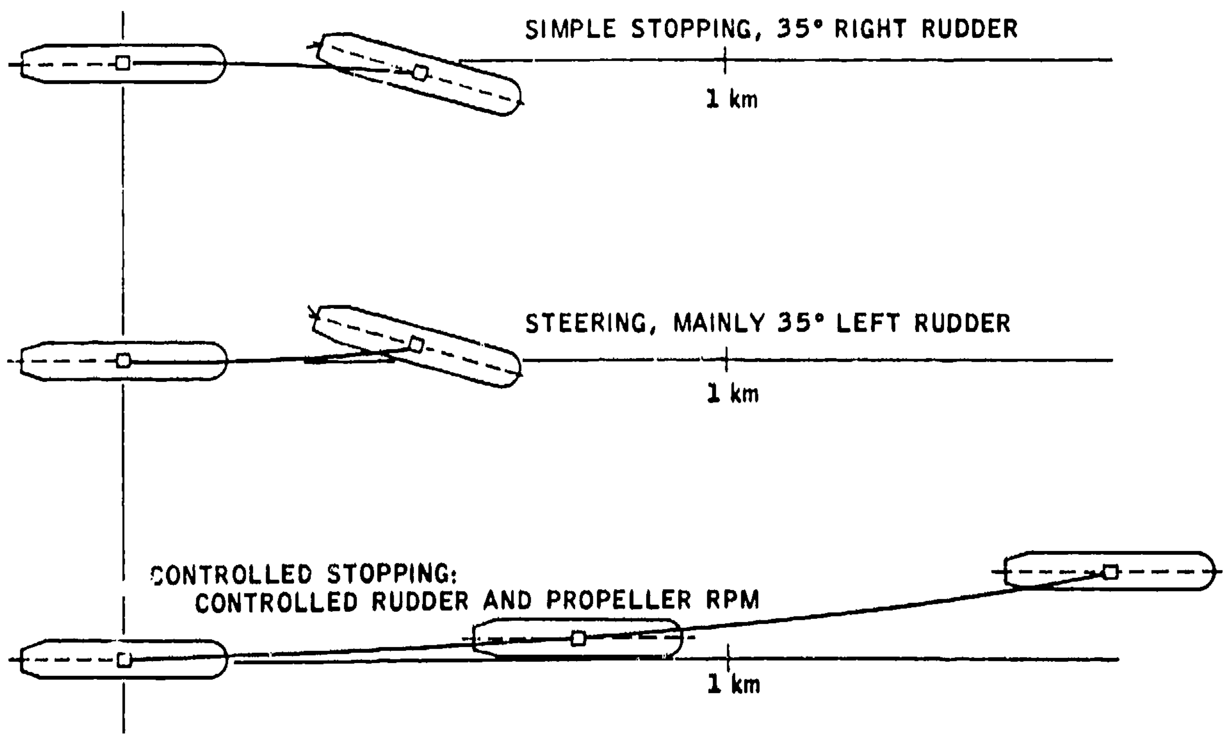

FIGURE 20. CONTROLLED, SIMPLE AND STEERING STOPS IN DEEP WATER

Approach Speed 3.5 Knots, 45 Rpm Astern Except For Controlled Stop

45 rpm astern. The result, shown in the middle of the Figure 20, indicates little change. Finally, the master was asked to stop the vessel using both rudder and engine speed as he thought best to maintain the original heading, with stopping distance being a secondary objective. The resulting maneuver is shown at the bottom of the Figure 20, with a head reach of about three times that of the simple stop or the steering stop. Examination of the time history of the controlled stop (Run No. 11513) shows that when 35 degrees left rudder was found insufficient to hold the heading steady (at about 140 seconds into the maneuver) the master alternately used rpm astern, ahead and stopped to control the heading. Table 6 shows

that, although the heading was held virtually constant, the vessel gradually drifted to the left a distance even greater than the maximum deviation of the stern swinging to port in the 35 degree right rudder case.

TABLE 6
RUDDER & RPM CONTROL EFFECT ON STOPPING (DEEP WATER)

Run No.	Rudder Angle	RPM Astern	V Approach, Knots	Max. Hdg Change, Deg.	Head Reach, m	Max. Lat.** Dev., m
8513	35° Right	45	3.5	18° Right	490	49 Left
10513	Steered*	45	3.4	16° Right	495	88 Left
11513	Steered*	Varied	3.5	2° Left	1650	195 Left

* Mainly 35° left rudder.

** Swept path, extreme.

A similar trial run was made in shallow water (h/T = 1.2) without as much attention to maintaining heading (Appendix F, Run No. 11512). In that case, stopping distance relative to Run No. 8512 without engine maneuvering increased by about 80% (when converted to 3.8 knots approach speed). However, ship's heading diverged as much as 17 degrees to starboard before ending at 7 degrees starboard when forward motion stopped.

ADDITIONAL RESULTS

Ship Speed Effects On Rudder Maneuvers With Constant Rpm

The effect of ship speed on the path geometry of a large tanker is usually considered to be small. This is because tankers normally operate at relatively low Froude number, meaning that wave making and heeling are small. For this reason hull, propeller and rudder hydrodynamic forces all vary roughly proportional to the square of ship's speed through the water, and produce geometrically similar maneuvering paths.

Two trial runs of the present series were scheduled in an attempt to verify this. The first was Run No. 4512, a turning circle with 35 degrees left rudder from 5.0 knots in shallow water. This is compared to Run No. 4712, which is the same except for the approach speed of 7.0 knots. Unfortunately, the 5 knots approach speed (and slower in the turn) allowed significant path distortion due to water current set and

drift. Also, the measured rudder angle in the 7.0 knot trial was 36 degrees instead of 35 degrees left. Nevertheless, the results, which are seen in the time-history and path plots of Appendix E, show nothing that strongly contests the assumption that path geometry is independent of speed. Turning indices are summarized in Table 7 below:

TABLE 7 SPEED EFFECT ON TURNING CIRCLE IN SHALLOW WATER (h/T=1.2)

Run Number	Rudder Angle	Approach Speed, Knots	Advance at 90°, meters	Transfer at 90°, meters	Tact. Dia. at 180°, meters
4512	35° L	5.0	1197	668	1631
4712	35° L	7.0	1189	555	1564

The second comparison was made in a deep water turn with 35 degrees right rudder, Table 8. Run No. 3723 was from an approach speed of 7.8 knots, and Run No. 3213 from 10.0 knots. Again the water current (0.73 knots in the 7.8 knot approach case) casts some doubt on the validity of the comparison, but the results do not seriously contest the assumption of path independence of ship speed. In fact, the tendencies are in the opposite direction from those of the previous comparison.

TABLE 8 SPEED EFFECT ON TURNING CIRCLE IN DEEP WATER (h/T=4.2).

Run Number	Rudder Angle	Approach Speed, Knots	Advance at 90°, meters	Transfer at 90°, meters	Tact. Dia. at 180°, meters
3723	35° R	7.8	1017	361	924
3213	35° R	10.0	1138	567	1001

Water Current Effects

Although path plots of all maneuvers were "corrected" to a nominal still water condition, as described in Apendix E, set and drift are a fact of life in slow speed maneuvers. Shiphandlers must be skilled in adapting to non-uniform and time varying currents for the same reason that current corrections cannot be accurately made even in controlled experiments such as these. The degree of water current non-uniformity in these trials is described in Appendix E. Here we need only point out that the importance of current effects can, if desired, be assessed by comparing "as measured" and corrected path plots shown in Appendix F.

A particular example is the deep water turning circle of Run No. 3723, where current speed is about 10% of the 7.8 knot approach speed to the

maneuver. Approach heading was 272 degrees, T. Had path results not been corrected for set and drift, the turning indices would have been affected as seen in Table 9.

TABLE 9. EXAMPLE OF CURRENT EFFECT ON TURNING INDICES

Condition	Advance, m, at 90°	Transfer, m, at 90°	Tact. Dia., m, at 180°
Uncorrected	880	420	1007
Corrected for set toward 66.5 degrees T, 0.73 knot drift	1017	361	924
Error, relative to corrected value	-14%	+16%	+9%

The above results should be kept in mind when asking ship masters to perform ad hoc maneuvering trials at sea. Of course, water current drift errors will be exaggerated in stronger currents unless ship speeds are correspondingly faster.

Propeller Asymmetry Effects

The effects of propeller asymmetry of a single-screw ship were already seen in the data on water depth effects on turning and stopping maneuvers. The comparisons of Table 10 only summarize asymmetry effects on turning maneuvers made in different water depths. The degree by which the dimensions of right turns exceed those of left turns is shown below each pair.

Although the exact rudder angles desired for good comparisons were not always achieved, it is apparent that turning circles to the left required somewhat smaller areas than those to the right.

The accelerating turn shows a larger effect of propeller asymmetry, as seen in Figure 21.

Visual Observations During Maneuvers

Heel in Turning: Limited bottom clearance in the shallow water site caused particular attention to be paid to any dynamic heeling that

TABLE 10. PROPELLER ASYMMETRY EFFECTS ON TURNING CIRCLES

Run Number	Water Depth	Rudder Angle, °	Advance, meters at 90° Heading	Transfer, meters at 90° Heading	Tact. Diameter meters at 180° Heading
7412	Shallow	36° L	1189	555	1564
3722	Shallow	34° R	1182	707	1591
	DIFFERENCE		-1%	+27%	+ 2%
4711	Medium	33° L	916	384	1073
3711	Medium	36° R	990	407	1073
	DIFFERENCE		+8%	+6%	0%
4713	Deep	35° L	1006	309	894
3723	Deep	36° R	1017	361	924
	DIFFERENCE		+1%	+17%	+3%

might have brought the bilge closer to the bottom. However, no measurable heel was detected with the ship's existing pendulum inclinometer. Sightings were therefore made from a central point in the wheelhouse, using wheelhouse side window edges and the clear horizon as guides. This rough check, made in the medium depth area, indicated that heel due to turning at 7 knots, with 35 degrees rudder, did not exceed one half degree. Also, heel was toward the center of the turn and not outboard as anticipated. This may have resulted from a higher dynamic water level on the outboard side of the ship which would have more than corrected the opposing inertial heeling moment.

Sinkage and Trim: Vessel sinkage and trim were not measured in the trials, although pneumatic draft gauges installed in the ESSO OSAKA were observed several times during maneuvers. On no occasion was more than 15 centimeters trim aft indicated, including during a 35 degree rudder angle turn from a 7 knot approach speed with 4 meters bottom clearance.

These indications are not taken as reliable, as we do not know the characteristics of pneumatic draft gauge readings as a function of ship speed or local drift angle. Regarding sinkage, according to a preliminary calculation, a total change of about 15 centimeters was expected with 4 meters bottom clearance. However, even with good echo sounding measurements it was not believed that the generally flat sea bottom was sufficiently uniform to measure sinkage.

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Rudder Angle	Advance at 90° Heading, m.	Transfer at 90° Heading, m.	Tactical Diameter at 180° Heading, m.
35°L	355	205	750
35°R	470	160	810
Difference	+32%	-22%	+8%

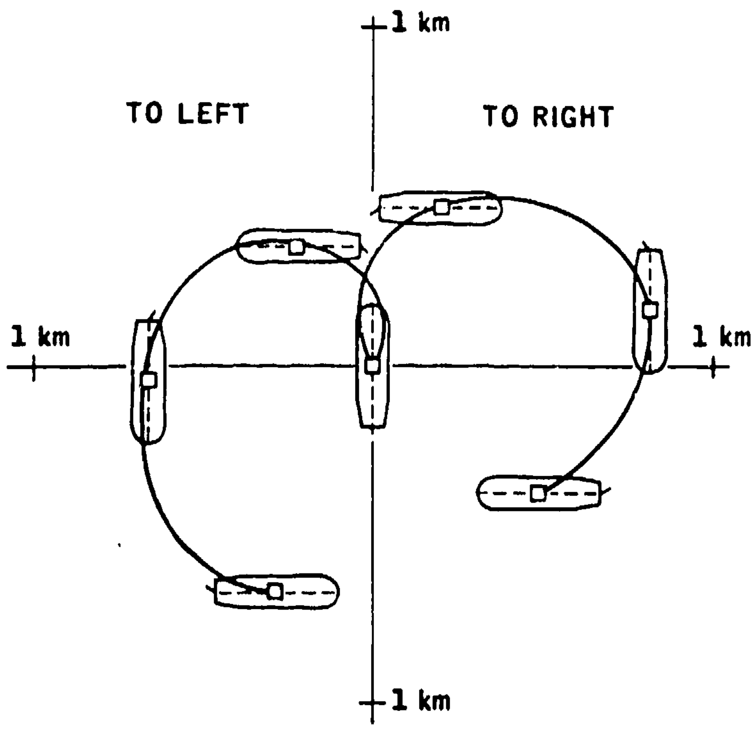

FIGURE 21. PROPELLER ASYMMETRY EFFECT ON ACCELERATING TURN, IN MEDIUM WATER DEPTH

From Zero Initial Speed, Zero To 56 Rpm, With 35° Rudder

Silt in Wake: Hard packed gray clay was observed by divers on the sea bottom and was collected from the anchor chain on deck. In addition, there was evidence of a bottom layer of fine silt or sand. The ship's wake was observed during turning maneuvers, and showed a bright yellow

path in the otherwise blue water. In fact the ship was observed to retrace its own path after completing more than 360 degrees of 540 degree turning circles in the medium and shallow water sites. Coast Guardsmen on patrol cutters also reported observing the wake from straight course running some distance behind the ship, although this was not evident from onboard. Divers reported reduced visibility near the sea bottom, also suggesting a finely silted bottom.

DISCUSSION OF RESULTS

GENERAL

The trial results clearly show that distortions of flow about a ship's hull in shallow water significantly affect maneuvering motions. The sketches of Figure 1 show why the cross-flow passing under a ship's bottom when maneuvering in deep water must, in very shallow water, be mainly constrained to pass around the ship's sides. In consequence, the combined effects of shallow water on side drift and turning in maneuvers greatly exaggerate the hydrodynamic side forces acting on a ship, and shifts the center of pressure aft towards amidships. Meanwhile, the relative effectiveness of the rudder is reduced because its center of pressure moves forward (References 12-16). Also, the rudder's effective aspect ratio, due to the presence of the seabottom, is increased much less in shallow water than is that of the hull. Recall that a ship's hull has a very low aspect ratio in deep water.

With this brief physical picture, some trial findings are discussed.

TURNING, Z-MANEUVER AND SPIRAL TEST RESULTS

Changes in turning circle characteristics and Z-maneuver indices with water depth are loosely related to the changes in dynamic stability that are indicated by spiral test results.

According to theory (References 12-16), and the present trials, the dynamic stability of a ship's hull (i.e. with controls fixed) first decreases when moving from deep to medium water depths and then increases again as water depth becomes very shallow. We therefore look for relationships between dynamic stability* and maneuvering in terms of turning ability and quickness of response, such as in checking a turn. In general these appeared in the present trial results, as follows:

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*With controls fixed. See discussion under Spiral Test in RESULTS.

The hull, with controls fixed, as interpreted from spiral test results, appeared to be marginally dynamically stable in deep water, slightly unstable in medium depth and stable in shallow water. Although dynamic (controls-fixed) stability is not directly related to directional stability it has some relationship to Z-maneuver and turning circle behavior. For example, the 1st yaw angle overshoot in the Z-maneuver increased from 9.5 degrees in deep water to 11.2 degrees in medium depth, and then reduced to 7.8 degrees in shallow water. Maximum lateral deviations, and advance at maximum lateral deviations also changed consistently with yaw overshoots. This suggests that the minimum dynamic stability in medium water depth is associated with the maximum Z-maneuver overshoot in the medium water depth. Also, the maximum swept turning diameter increased only modestly in medium depth (14%), but greatly in shallow water (63%) compared to deep water.

Of course, not too much should be read into the relationship between dynamic stability and maximum turning ability, since dynamic stability indications from the spiral test refer mainly to steady turning motions with small rudder angles, while maximum turning with large rudder angle is highly nonlinear.

On the other hand, Z-maneuver results relate more closely to quickness of response as indicated by the spiral test results. And, in fact, the Z-maneuver results reflect the reversal trend of the spiral results much more faithfully than do the changes in maximum turning diameters.

PROPELLER RPM EFFECTS ON HEADING CONTROL

The accelerating turns made in the medium and shallow water depths confirm facts well known to shiphandlers, i.e. that advance and tactical diameter can be reduced by "kicking ahead" with the propeller in a slow speed turn. The reason is that water flow past the rudder is quickly increased, while the hull hydrodynamic forces aiding or resisting the turn are not.

On the other hand, the coasting turns showed a directionally predictable decrease in turning ability when the propeller discharge flow was removed from the rudder. Much of the rudder was then put in a separated flow region behind the idling propeller. But perhaps of greatest significance is that the single-screw VLCC, once predicted to be virtually unmanageable in slow speed maneuvers, was able to turn reliably at slow speeds, even with the engine stopped.

Taken together, the above trial results emphasize that maneuverability is improved when rpm is increased and degraded when rpm is reduced. Knowing this, the prudent shiphandler will look for the slowest safe

speed in certain critical maneuvering areas. If then required to speed up, maneuverability will increase instead of being degraded if unexpectedly required to slow down.

The coasting Z-maneuver gave further evidence that the trial vessel could maneuver reliably and predictably with engine stopped, even at speeds as low as 1.4 knots. In all cases it appeared that the ship was still responding to rudder commands when the maneuver was terminated.

The trends of response to the coasting 20°-20° Z-maneuver closely follow those of the conventional 20°-20° Z-maneuver, as shown in Table 4. Both follow the trends expected from the spiral tests based on what has been learned about dynamic stability in different water depths. The results with engine stopped were actually better than expected, since the water flow about the ship's rudder must have been greatly reduced with the propeller dragging.

RUDDER AND RPM EFFECTS ON STOPPING

In general the strongest observed effect of shallow water on stopping was the much greater tendency for the ship's stern to swing to port as it came to a halt. A possible explanation is that the sea bottom tends to restrict the forward-directed propeller outflow (when stopping) causing more flow around the sides of the vessel, and therefore exaggerating the usual propeller asymmetry side force effects.

Although subjective, one of the more interesting trials was the controlled stopping maneuver; i.e., holding the heading constant throughout. It had been assumed that success would show a clear benefit of the controlled stop over simple stopping with constant astern rpm. Instead, the results showed that from a prudent slow approach speed, as is normally used in approaching a single point mooring (SPM), the simple stop developed smaller lateral deviation, and a much shorter head reach. This suggests that the only advantage of the controlled stop from a slow approach is that the desired heading is maintained. However, if the trial maneuver had been designed to maintain a desired straight trackline instead of heading, the trackline probably could have been achieved with substantially less lateral deviation than that of the simple stop. The controlled trackline also corresponds more closely to actual operations in a channel or approaching an SPM. The gradual drift of the ship to the left during the controlled stop may be explained by the following considerations:

a. With reversed propeller rotation, a side force to port develops causing the stern to drift to port. To counter this, left rudder is used.

b. If the sum of the side forces due to reversed propeller and left rudder are equal in magnitude, and have the same center-of-pressure, no lateral drift will result.

c. Lateral drift to port did occur, however, even though no heading drift occurred. Therefore, although the yaw moments due to astern rpm and left rudder angle cancelled each other, their side force contributions apparently did not. A possible explanation is that the center-of-pressure of rudder force is further aft than the center-of-pressure due to astern propeller rpm. The rudder force acting to starboard could then be smaller than the propeller side force acting to port, and this would result in a small drift to port, as observed.

SHIP SPEED AND WATER CURRENT EFFECTS

The corrected turning circle results from tests at different approach speeds show quite similar paths. This verifies that there is little speed effect on turning geometry at low Froude numbers (below 0.10 in these trials). However, with water current present, the slow speed maneuvers suffer much greater distortion than high speed maneuvers because of the translation of the current. This is seen in the comparison of trial runs Number 3723 and 3213 which are not corrected for current. Wind, if strong enough to be important, would also affect maneuvers at slow speed much more than those at high speed. For a given ship configuration and draft, the ratio of wind speed to ship speed is important. These facts are well understood by shiphandlers as they judge minimum safe maneuvering speeds. For further discussion of variable water current effects, see Appendix J.

COMPARISON WITH PREVIOUS MODEL AND SHIP DATA

As indicated in the Introduction, previous model and full-scale maneuvering trial data in shallow water were less than satisfactory. To illustrate this, Table 11 provides comparative data from available shallow water maneuvering trials of other VLCCs: ESSO BERNICIA (Reference 5) and MAGDALA (Reference 6); or from predictions made of ESSO BERNICIA maneuvers by Hy-A Laboratory in Lyngby, Denmark (using planar motion mechanism model tests for hydrodynamic coefficients and computer calculations; unpublished).

The comparisons show that while the model-based predictions of tactical diameters do not differ greatly from the ESSO OSAKA or other full-scale results, the Hy-A Z-maneuver 1st yaw angle overshoot predictions are much smaller than the results from the ESSO OSAKA. ESSO BERNICIA results also compare poorly.

Results of Hy-A model based computer calculations of ESSO BERNICIA spiral tests in different water depths predicted no loop in any of the

TABLE 11 COMPARISON OF ESSO OSAKA DATA

WITH PREVIOUS SHALLOW WATER RESULTS

Ship	Depth/Draft	Turning Circle Tactical Diameter (Ship-Lengths)
ESSO OSAKA (Present Trials)	1.2	4.9
	1.5	3.3
	Deep	2.8
MAGDALA (Ref. 6)	1.2	--
	1.5	3.5
	Deep	2.8
ESSO BERNICIA (Ref. 5*)	1.2	--
	1.6	2.8
	Deep	2.5
ESSO BERNICIA (HY-A PMM Model)	1.2	4.2
	1.7	2.2
	Deep	3.1

Ship	Depth/Draft	Z-Maneuver 1st Yaw Overshoot, (Degrees)
ESSO OSAKA (Present Trials)	1.2	7.8
	1.5	11.2
	Deep	9.5
ESSO BERNICIA (Ref. 5*)	1.2	--
	1.6	22
	Deep	17
ESSO BERNICIA (HY-A PMM Model)	1.2	2.5
	1.7	6
	Deep	--

*Speed of Approach 14.7 Knots

depth to draft ratio tested: of 1.2, 1.7 and 2.0. On the other hand, the ESSO BERNICIA trials (Reference 5) show almost identical loops in spiral tests in shallow water (depth/draft = 1.4) and deep water. In view of the present ESSO OSAKA findings, both of these results are questionable and, although some differences should be expected due to somewhat different hull and rudder configurations, these comparisons support the original contention that existing shallow water maneuvering trial data were inadequate at the outset of this program.

CONCLUSIONS

1. The present trials provided a quantity of information not previously measured regarding the maneuvering characteristics of a ship in shallow water. Both research and operational type maneuvers keyed to large tankers were made. In the process it was found that the single-screw ESSO OSAKA, a 278,000 deadweight ton tanker, was able to maneuver reliably and predictably in all tested water depths; even with engine stopped, as when simulating maneuvers after a propulsion failure.

2. Distortions of the flow about the hull of a ship in shallow water were found to have important effect on maneuvering motions. For example, trial measurements indicated that:

- In shallow water, turning circle tactical diameters will increase by as much as 75% with 20% underkeel clearance, while drift angle and related speed loss will reduce relative to turning in deep water. With 50% bottom clearance, the changes from deep water turning are much less. The effects on turning circle diameter are significantly greater than expected, based on previous model predictions and full-scale trials.

- Checking and counterturning ability are reduced as water depth decreases to an intermediate depth (50% bottom clearance in the trials) and then, with 20% bottom clearance, these qualities increase to better than in the deep water case. This is closely related to the apparent reversal in maneuvering dynamic stability (with controls fixed), as is suggested by the present spiral test results. Again, previous model and full-scale trials in shallow water failed to disclose this.

- The greatest effect of decreasing water depth on the stopping of a single screw tanker, from slow speed, appears to be an increase in yaw rotation to the right as it comes to a halt. In the present trials the heading change increased from 18 to 50 to 88 degrees in deep, medium and shallow water, respectively.

- Accelerating turns increased in diameter in shallow water, but to a lesser extent than did the conventional turns. On the other

hand, coasting turns suffered a trend reversal. The widest coasting turn path was in the medium water depth and the least was in deep water.

3. Trials to show the effects of a shiphandler's control of propeller rpm during maneuvers provided useful insights. For example:

- Accelerating turns confirmed that "kicking" ahead the rpm when moving at reduced speed significantly increases turning ability.

- The coasting Z-maneuver demonstrated conclusively that the subject VLCC could continue maneuvering in response to rudder actions even with the engine stopped. It also showed that this very large vessel could continue maneuvering while coasting down to speeds less than 1.5 knots. This result should be encouraging to those concerned with the maneuvering safety of tankers. The magnitudes of yaw angle overshoots, although different from those with engine operating, showed directionally similar tendencies with respect to effect of water depth.

- As expected, rudder control of the single-screw vessel was eventually lost during stopping maneuvers with constant astern rpm, although the vessels' final orientation was to some extent affected by early rudder action. Although the ship's heading could be maintained constant during a "controlled" stop by using various engine orders, it was at the expense of increased stopping distance and greater lateral drift.

Taken together, the points of Conclusion 3 emphasize that maneuverability is improved when rpm is increased and degraded when reduced. Knowing this, the prudent shiphandler will usually look for the slowest safe speed in a critical maneuvering area. If then required to speed up, maneuverability will increase instead of being degraded if unexpectedly required to slow down.

4. Other technical conclusions, which are mainly confirmatory, follow below:

- Speed of approach has a minor effect on the geometry of the conventional turning circle of a large tanker within the maneuvering speed range (5 to 10 knots).

- Asymmetry of maneuvers to the left and right hand, caused by single-screw propeller rotation, is greatest when rpm ahead or astern is large relative to ship speed. This is the case in slow speed stopping and in accelerating turns. It is minor in the case of conventional turns.

5. Technical data from the present trials should be adequate for validating model and analytical methods for predicting ship maneuvering in deep and shallow water under operational type conditions at slow speeds, and for meeting all of the other objectives of the program.

RECOMMENDATIONS

After comparing the results and conclusions of the present trials against the objectives, it is recommended that the sponsors encourage and support efforts to:

1. Validate present-day procedures for developing mathematical models by performing experiments with captive models, making computer predictions, comparing these with the present full-scale trial data and then, if necessary, improving the prediction techniques.

2. Establish the validity of large hydraulic models in applicable areas. These models, which include large self-propelled model ships, are being used under conditions where irregular side and bottom boundaries and water currents are believed important.

3. Determine to what extent full-scale trial data can be useful for developing maneuvering information for posting in the wheelhouse of vessels, as is recommended by IMCO and required by U.S. Coast Guard.

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APPENDIX A

SPONSORS, SUBCONTRACTORS, & PARTICIPANTS

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